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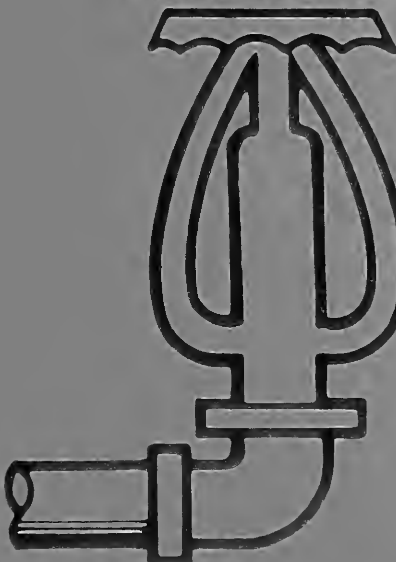
INVESTIGATION OF IMPROVED SENSOR/ACTUATOR CONCEPTS FOR RESIDENTIAL FIRE SPRINKLER SYSTEMS

FINAL REPORT



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INVESTIGATION OF IMPROVED SENSOR/ACTUATOR CONCEPTS FOR RESIDENTIAL FIRE SPRINKLER SYSTEMS

FINAL REPORT

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16. Abstracts

An information search of potential techniques to sense residential fires and activate water sprinklers was made. Several novel approaches to increasing sprinkler sensitivity, reducing spurious action, and reducing cost were selected for laboratory development. Transistor and thermal resistor based electronic fire sensors were built to actuate a solenoid and pyrotechnic valves. A temerature-sensitive, shape-recovery, nickel titanium alloy was used to build a simple, modified, conventional link sprinkler and a sprinkler that automatically turns off after use. Controlled temperature, temperature response, water flow, and hydrostatic leakage testers were built. The hardware was tested and recommendations were made for the development of future systems.

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FINAL REPORT

on

INVESTIGATION OF IMPROVED SENSOR/ACTUATOR CONCEPTS FOR RESIDENTIAL FIRE SPRINKLER SYSTEMS

USFA Grant No. 79038

to

U.S. Fire Administration
Federal Emergency Management Agency

from

BATTELLE
Columbus Laboratories

January 31, 1980

INTRODUCTION

It has been estimated that approximately 8,000 persons die each year in the United States as the result of fires. In addition, many persons suffer serious injuries, and extensive property damage occurs as a result. The vast majority of these losses occur in residential fires; thus, home fire safety is of vital concern to each of us. Many of these deaths and injuries, as well as a considerable portion of the property damage, could be prevented if adequate fire protection systems were installed. For example, in one study of 117 residential fires, it was estimated that at least 157 of the 171 deaths involved could have been prevented, and 181 of the 189 injuries could have been eliminated. The resultant property damage of these fires, which was estimated at $2.8 million could have been lowered to between $396,000 to $912,000, depending on whether a sprinkler or smoke alarm fire protection system (respectively) were used.

There are a number of things which can be done to improve residential fire safety and these approaches have been dealt with extensively in the literature. For example, during the construction phase, techniques and materials can be used to make the residence fire-resistive, although the contents must

be given similar considerations. Also, the residents can exercise care and avoid dangerous practices which might cause fires to develop. The careless use of smoking materials is a factor in 25-30 percent of all single-family dwelling fire deaths. In spite of these technological and educational possibilities, residential fires will likely occur in the foreseeable future. It is the objective of this program to investigate concepts that could improve residential fire safety through rapid response fire sprinkler systems.

Numerous investigations of the use of automatic sprinkler systems for residences have been conducted, and they are in agreement that these systems provide the best fire safety currently available. In Europe and the United Kingdom, sprinkler systems are in common use and have conclusively demonstrated their value. In Australia and New Zealand, during fires in offices, hotels, and other light-hazard occupancies where sprinkler systems were installed, only one fatality occurred during a 80-year period.

One of the criticisms commonly voiced against the residential use of automatic sprinkler systems is the high cost associated with the high water-discharge rates which are required by many current codes. Work at BCL as well as other facilities has shown that it is possible to control residential fires with relatively low discharge rates. The water rate is small enough to make sprinkler systems for residential buildings economically acceptable. The approaches needed to promote low-water-usage sprinkler systems for residences are reasonablly well known at this time.

Another major problem with the residential use of automatic sprinkler systems is the possibility of needless actuation. It is essential that any automatic sprinkler system for home use be designed so that it is sufficiently sensitive to detect fires before they become well developed.

The spurious actuation of smoke detectors and burglar alarms has been widely noted. However, while this is primarily a nuisance for these systems, such actuation for a residential sprinkler system could result in greater financial loss because of water damage than an actual fire.

The automatic fire-protection system, depending on configuration, can have numerous components, including fire sensors, electrical power supplies,

alarms, wiring, sprinklers, sprinkler actuators, piping, and water supply. The two most important functions of an automatic fire protection system are fire detection and fire containment. Detection is required to initiate containment and alarm occupants; containment is required to allow occupant escape and reduce property damage. On this basis the Battelle approach is directed toward the system components that detect and protect, namely sensors and actuators. Battelle believes that application of new technologies to sensors and actuators is the critical requirement for innovation. Significant advances have been made with all the system components; however, sensors and actuators are the basic components around which the entire system is designed. Therefore, innovation in these areas will affect all components and allow design improvements to permeate the entire system.

An automatic fire protection system designed for mass residential usage must be comprised of small, inexpensive, simple parts. Each part must be designed for mass production and be of specific reliability. The system must provide detection of the fire before dangerous heat levels or gas concentrations are reached and must activate the minimum water supply required for containment. Basic requirements are:

- The need for earlier fire detection
- The need for minimum spurious actuation
- The need for reliable operation
- The need for low cost.

Battelle has selected certain technologies that have potential for solving specific present inadequacies. Battelle searched the literature and available sources for techniques of fire sensing and sprinkler actuation. Techniques were evaluated and compared with each other analytically. Technologies selected for laboratory development were electronics, Mitinol, and pyrotechnics. Concept models were built and compared with commercial sprinklers in temperature, water flow, and hydrostatic leakage tests. Several results are very encouraging and point the way toward a marketable design. This report contains the results of our technology search, a description of the hardware models, performance testing results, conclusions as to applicability of the sensor/actuator concepts, and recommendations that outline the technical activities required to refine the best program concepts into marketable equipment.

SUMMARY

The purpose of this program is to determine the extent to which the sensor and actuator functions of residential sprinkler systems could be improved at a reasonable cost. Ultimately, improved components may result in increased unit costs; however, total installed cost could possibly be reduced due to component location and materials. Concepts were originated by an inhouse search of previous related work and by a literature and telephone survey. The various techniques for sensing and actuation were evaluated according to sets of criteria determined by the project team. The criteria were based on improved and advanced features for residential sprinkler systems that would reduce costs and increase performance. The best techniques were selected on this basis, and the hardware development of new components for each technique was undertaken.

Concepts selected were electronic temperature sensing, pyrotechnic and solenoid valve actuation, combined sensing/actuation by Nitinol*, actuation by electrical heating of a Nitinol element, and combined sensing/actuation by a modified eutectic alloy based linkage. The techniques were tested under conditions of controlled temperature and hydrostatic pressure. In addition, measurements of thermal response time and water flow were made. The same battery of tests was applied to selected commercial sprinklers, and performance comparisons were made.

The experimental results indicate that initial models of electronic and Nitinol based sprinklers can bracket the performance of conventional systems in selected tests. Thermal response times have been decreased without lowering threshold operation levels. Critical water flow and hydrostatic sealing capabilities have been retained, although continued development in these areas is recommended. While the electronic components are more expensive than the Nitinol components, both systems are built using relatively low-cost pieces. Both systems are recommended for continued development and full-scale testing.

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*A nickel titanium alloy that can have a transformation induced shape change over a prespecified small temperature range.

SURVEY OF POTENTIAL TECHNIQUES FOR RESIDENTIAL FIRE SENSING AND SPRINKLER ACTUATION

The concepts were obtained from commercial manufacturers and associations, government agencies, and Battelle staff. Sources also included Thomas Register and the Engineering Index. Two categories of concepts were sought: fire sensors and sprinkler actuators. Sixteen concepts for fire sensors and eight concepts for sprinkler actuators were identified and are evaluated herein. Each concept employs a different principle of operation, and the various concepts are presently in stages of development ranging from an idea only to a manufactured product that is widely used. The objective of this assessment was to select concepts for development that, in Battelle's judgment, will most improve the performance and marketability of residential sprinkler systems.

Evaluation Criteria

The criteria represent major performance attributes that Battelle considers applicable to residential fire sprinkler systems. The criteria were selected to each have the same relative order of importance. The fire sensor and sprinkler actuator criteria groups are ranked in slight descending order of importance in Tables 1 and 2. When the criteria were used to rank concepts, no weight loading was given to any particular criteria. The purpose of the evaluation was not to judge small details of one system over another, but to identify major technology groups with the highest potential for performing best in most or all of the required attributes.

TABLE 1. FIRE SENSOR CRITERIA

(1) Response Time
(2) False Alarm Rate
(3) Cost
(4) On-Off Capability
(5) Requirements for Electrical Power or Auxiliary Equipment

TABLE 2. SPRINKLER ACTUATOR CRITERIA

(1)	Reliability
(2)	Cost
(3)	On-Off Capability
(4)	Requirements for Electrical Power on Auxiliary Equipment

How Each Technique Works

The below descriptions feature the principle of operation for each technique and its developmental status as a fire sensor or sprinkler actuator at the time of survey. Categories are provided for both sensors and actuators. Some techniques appear in both categories, which indicates the existence of a combined sensor/actuator; i.e., a frangible glass bulb or fusible link sprinkler. Examples of a sensor only would be electronic temperature sensors or smoke detectors. Examples of an actuator only would be a solenoid or pyrotechnic actuated valve. Following the descriptions are rank comparison tables of all the concepts based on the previous criteria.

Sensors

1. Frangible Glass Bulb. The bulb, which contains a high vapor pressure liquid and a small air bubble, is used as a strut to maintain a normally open water passage. When exposed to heat, the liquid expands, compressing the air bubble. When the bubble is completely absorbed, there is a rapid increase in pressure, shattering the bulb and allowing water flow. The desired temperature rating is obtained by controlling the size of the air bubble relative to the amount of liquid in the bulb. Glass bulb sprinklers are widely used, relatively inexpensive, and reliable, but do not have the capability to turn off after use.

2. Fusible Link. This is the most common technique used to sense fires and actuate sprinklers. Links contain eutectic alloys which melt

rapidly at a predetermined temperature. The eutectic is used to secure a spring linkage under tension. When the alloy melts, the spring action is used to open a water passage.

3. Electronic Temperature Sensors. Thermistors, thermal resistors, and transistors are available which are temperature sensitive and can drive analog outputs. Relatively inexpensive circuit components can be used to sense threshold or rate-of-rise and trigger an actuator to remain on for about ten minutes after the rate-of-rise or threshold fall below preset critical values. A practical, inexpensive, and safe way to power the electronics is utilizing available 110 VAC and a transformer rectifier to produce 24 VDC for the power supply. The transformer rectifier is small and can be centrally located in the center volume of a protected area. Long-term power drains are negligible, and the 24 VDC provides reduced human electrical hazards.

4. Electronic Gas Sensors. These devices require a power supply. They are inexpensive, but are prone to activation by non-hostile sources such as alcohol, after-shave, or perfume. An example is the Taguchi Gas Sensor, which is a metal oxide semiconductor responsive to state of oxidation. It can sense carbon monoxide and hydrocarbon levels, or a lack of oxygen.

5. Photoelectric and Gas Ionization Smoke Detectors. These devices require a power supply and are widely used as residential fire alarms. Smoke detectors operating on the photoelectric principle give somewhat faster response to the products generated by fires of low energy (smoldering), as these fires generally produce large quantities of visible (larger particle) smoke. Smoke detectors using the ionization principle provide somewhat faster response to fires of high energy (open flaming), as these fires produce the smaller smoke particles which are more easily detected by this type of detector. Neither principle can discriminate between hostile or non-hostile smoke, which may cause spurious action of a sprinkler system; moreover, decreasing sensitivity of such devices to small fires results in longer response times to all fires.

6. Nitinol. Devices powered by Nitinol do not require a power supply. Energy can be stored in the nickel titanium alloy by physically deforming it to a calculated shape at room temperature. If the shape is heated beyond a pre-set temperature level, it will exert itself up to 80,000 psi by "springing" back to its original shape. Any temperature level can be set between -60 °F and 250 °F by varying compound amounts of nickel and titanium which make up the alloy. Nitinol is used for aircraft hydraulic tubing connectors in hard-to-reach areas where they can simply be slipped on by hand then fastened by application of a hot-air gun. Nitinol has also been used in heat motors and thermally activated latches. The "memory" of Nitinol was discovered about 15 years ago at the U.S. Naval Ordnance Laboratory, hence the name Nitinol is an abbreviation for Nickel Titanium Naval Ordnance Laboratory. It can be made in any form, and the large-volume material cost of a piece comparable to a fusible link is less than one dollar. The major advantage of Nitinol over eutectic is that, while both can be made to activate at a preset temperature, the Nitinol is four to five times stronger. Therefore, Nitinol sensors can be built smaller and more heat-sensitive. Also, the action of Nitinol is repeatable and would lend itself to automatic on-off operation, whereas fusible eutectic alloys are intended for one use only.

7. Ultraviolet and Infrared Flame Detection. Flame detectors optically sense either the ultraviolet (UV) or infrared (IR) radiation given off by flames or glowing embers. Flame detectors have the highest false alarm rate and the fastest detection times of any type of fire detector. Detection times for flame detectors are generally measured in milliseconds from fire ignition. Flame detectors are generally only used in high-ceiling areas and any other areas where hazardous atmospheres in which explosions or very rapid fires may occur. Flame detectors are "line of sight" devices, as they must be able to "see" the fire, and they are subject to being blocked by objects placed in front of them. However, the infrared type of flame detector has some capability for detecting radiation reflected from walls. Presently, UV and IR detectors are complex systems of cost beyond a typical homeowners budget; they also require a power supply.

8. Microwave (Radar). An antenna, radiometer, and indicator are used to detect microwave emissions from hot objects. Detectable microwaves can penetrate wood, asbestos, and roofing materials. These systems require a power supply and are expensive. The Chasek Engineering Co. of Stamford, Connecticut proposes to use microwave detection as a fire-fighting technique to find the "heart" of a fire.

9. Continuous Line Type. Several configurations of this type sensor are commercially available. One type of line detector uses a pair of steel wires in a normally open circuit. The conductors are insulated from each other by a thermoplastic of known fusing temperature. The wires are under tension and held together by a braided sheath to form a single cable assembly. When the design temperature is reached, the insulation melts, contact is made, and a signal is generated. Following a signal, the fused section of the cable must be replaced to restore the system.

10. Bimetallic. When a sandwich of two metals having different coefficients of thermal expansion is heated, differential expansion causes bending or flexing towards the metal having the lower expansion rate. This action can close a normally open circuit or activate a water valve. Bimetals are used for the operating elements of several types of fixed temperature detectors. These detectors are generally of two types: the bimetal strip and the bimetal snap disc. Drawbacks to the strip type of device are its lack of rapid positive action and its susceptibility to false alarms from vibration or jarring, particularly as the rated temperature is approached. Snap-disc devices are not as sensitive to false or intermittent alarms as the bimetal strips. Most thermal detectors using bimetal, Nitinol, or expanding metal elements have the desirable feature of automatic mechanical reset after operation when the ambient temperature drops below the operating point.

11. Pneumatic. The increased pressure of gas heated in a closed system can be used to generate a mechanical force which will operate signal contacts in a pneumatic fire detection device. In a completely closed system such as a bellows, actuation will occur strictly from a slow change in

ambient temperature, regardless of the rate of temperature change. Some pneumatic detectors in use today provide a small opening to vent the pressure which builds up during slow changes in temperature. The vents are sized so that when the temperature changes rapidly, such as in a fire situation, the pressure change exceeds the venting rate and the system is pressurized. These systems are generally sensitive to rates of temperature rise exceeding 15 °F per minute. The pressure is converted to mechanical action by a flexible diaphragm. This principle has been combined with fusible and bimetallic sensors to create combined threshold and rate-of-rise detectors. This type sensor may or may not require a power supply to drive an actuator.

12. Rate Compensation. This detector uses a metal cylinder containing two metal struts. These struts act as the signal contacts and are under compression in a normally open position. The outer shell is made of a material with a high coefficient of thermal expansion, usually aluminum, while the struts, usually copper, have a lower expansion coefficient. When exposed to a rapid change in temperature, the shell expands rapidly, relieving the force on the struts and allowing them to close. Under slowly increasing temperature conditions, both the shell and struts expand. The contacts remain open until the cylinder, which expands at a greater rate, has elongated sufficiently to allow them to close. This closure occurs at the fixed-temperature rating of the device.

13. Thermocouple. This common temperature-measuring device is driven by the voltage change with temperature change that occurs between two attached dissimilar metals. It requires the use of highly accurate auxiliary (Wheatstone bridge) equipment and is, therefore, too expensive.

14. Ultrasonic. Such a device could measure the change in sound propagation speeds of material with temperature changes. It would be complex and expensive.

15. Submicron Particle Detectors. During the earliest stages of thermal decomposition, in the pyrolysis or precombustion stage, large numbers

of submicrometer size particles are produced. These particles fall largely in the size range between 0.005 and 0.02 micrometers. Although ambient conditions normally find such particles in concentrations from several thousand per cubic centimeter in a rural area to several hundred thousand per cubic centimeter in an industrial area, the presence of an incipient fire can raise the submicrometer particle concentration sufficiently above the background levels to be used as a fire signal.

The Defense Division of Brunswick Corporation has developed an incipient fire detector which will instantly sense and signal the invisible beginnings of a fire condition. Utilizing a unique aerodynamic separation process, the detector discriminates only the submicron products of pyrolysis and is unaffected by extraneous contaminants such as dust. The incipient fire detector, along with ancillary fire suppression systems, has been procured for the U.S. Space Shuttle Orbiter and the European Spacelab manned spacecraft. To extend the utility of the incipient fire detector, Brunswick has developed a "system" arrangement, with multiple remotely located detectors tied to a central monitor-controller unit to create a comprehensive hazard protection and control system which has application in aircraft, ship, and critical facility installations. Presently, this and other submicron particle measurement devices are not practical for widespread residential use due to the cost of components.

16. Pyroelectric. Most piezoelectric devices today are based on certain crystals which, when deformed by pressure, generate an electric charge. The phenomenon is due to the electrically polar nature of the crystals. That is, they contain positively and negatively charged ions which separate when the crystals are subjected to stress. A certain class of piezoelectric materials known as piezoelectric polymers generates an electric charge with a change in temperate as well as with a change in pressure. This pyroelectric phenomenon may be applicable to fire sensing. Transducers using conventional piezoelectric materials usually have metal bases and housings and require threaded holes or specially ground flat surfaces of appreciable area for mounting. Polymer transducers, on the other hand, usually consist only of the active material and a metal lead. The finished film can be attached to

curved, twisted, or pliant surfaces. Piezoelectric polymers are relatively inexpensive and can be obtained from Pennwalt Corporation, in King of Prussia, Pennsylvania.

Actuators

1. Frangible Glass Bulb. This combined sensor/actuator is described as Item 1 of the previous section.

2. Fusible Link. This combined sensor/actuator is described as Item 2 of the previous section.

3. Bimetallic. This sensor and/or actuator is described as Item 10 of the previous section. An example of a bimetallic snap-disc actuator is the Grinnell on-off "Aquamatic" sprinkler. The snap disc drives the pilot of a pilot operated valve. This industrial sprinkler provides high water flow and an automatic turn-off feature; however, a model for residential use should have faster thermal response. This might be accomplished by down-sizing the flow components, thereby allowing the disc actuator to be less forceful, thinner, and more heat-sensitive.

4. Nitinol. This sensor and/or actuator is described as Item 6 of the previous section. Nitinol can be used to trip a spring-loaded valve linkage similar to a conventional fusible link. Or Nitinol can be spring-loaded itself so it is recycleable between hot and cold shapes to provide an on-off feature. For example, a piece of Nitinol of length A may be spring-tensioned so its length is A + X. When heated beyond a preset temperature, the Nitinol returns X amount to its pretensioned length A, thereby actuating a valve or valve linkage. When the Nitinol cools back below the preset temperature , the spring once again can tension the Nitinol back to length A. Nitinol can cycle the X amount repeatedly during each temperature cycle without degradation. Therefore, Nitinol actuated sprinklers could be reusable.

<u>5. Powered Nitinol</u>. Some devices have been built that use electrically heated Nitinol for actuation. The Nitinol can be heated by a separate electric heating element, or the Nitinol can be heated by passing an electric current through it. For example, Nitinol might replace the coil and moveable core of a solenoid. The relatively low electrical resistance of Nitinol requires that direct electric heating be accomplished with relatively high amperage. Battelle built an electric-actuated, pilot-operated, on-off Nitinol valve, but experienced difficulties in powering the Nitinol directly using miniature electronic circuits, as the current requirements were too large for feasible electronic components.

<u>6. Pyrotechnic</u>. Pyrotechnic actuators are available in Germany to turn on sprinklers. Conceivably, an actuator could be built with two pyrotechnic devices. One turns the sprinkler on, the other turns the sprinkler off upon command of an electrical signal. Pyrotechnics are usable only once. They consist of a sealed expandable housing containing a small amount of explosive and electrical resistance wire that fires the device when current is applied and expands the housing. Typical pyrotechnic actuators are one-eighth inch in diameter and less than three-quarters of an inch long. Upon firing, they extend to over an inch long and create a twenty-pound force. These devices are simple and low in cost.

<u>7. Solenoid Valve</u>. This type actuator is controlled electrically by producing an electromagnetic force to open and close a valve. Solenoid valves are presently used in some advanced fire protection systems. The applicability of solenoids to widespread residential use is mainly contingent on cost, as these devices are fairly expensive. A typical solenoid valve that can be used in residential applications costs $30.

<u>8. Bellows</u>. This type actuator is similar in principle to a sealed pneumatic sensor. The increased pressure of gas when heated in a closed system is used to generate a mechanical force to open a valve. Typically, thin stainless steel sheets are fabricated into a cylindrical bellows. Bellows are used to automatically open a dry-chemical fire extinguisher made by

Porta-Matic Fire Extinguisher Corporation in Northvale, New Jersey. Bellows could be made to turn a water valve on and off repeatedly but would require mechanical amplification to function. Such devices would not require a power source, but they are normally expensive to fabricate.

Comparison of Techniques

Table 3 compares the sensor concepts; Battelle selected concepts ranked first, second, and third for hardware development. Table 4 compares actuators; Battelle selected concepts ranked first, second, third, and fourth for hardware development. The powered Nitinol hardware (third ranked actuator concept) was not successful in the hardware development stage. The solenoid (eighth ranked actuator concept) was selected as a backup concept, as it was the only other actuator concept that could work in conjunction with an electronic temperature detector fire sensor. Models for each selected concept were built on a best efforts basis. The next section describes each model. Battelle used the ranking to select hardware development thrust areas that indicated the highest potential performance improvements per development cost. Also, Battelle concentrated its efforts on concepts that are not in common use but appear to be technically novel. As the comparison is biased to novel concepts, only simple numerical ranking techniques were used in preparing the ranking charts. Tables 3 and 4 should not be construed as a final or conclusive judgment of the relative merits of any one technique over another.

TABLE 3. RANK COMPARISON OF FIRE SENSOR CONCEPTS

Score Legend: 3 = Good, 2 = Fair, 1 = Poor

Rank	Sensor Type	Criteria: Response Time	False Alarm Rate	Cost	On-Off Capabilities	Extra Power or Equipment Requirements	Total Score
(1)	Nitinol	3	3	3	3	2	14*
(2)	Electronic Temperature	3	3	3	3	1	13*
(3)	Fusible	2	3	3	1	3	12*
(4)	Frangible Glass Bulb	2	3	3	1	3	12
(5)	Bimetallic	3	3	2	3	1	12
(6)	Pyroelectric	2	3	2	3	2	12
(7)	Rate Compensation	2	3	2	3	1	11
(8)	Thermocouple	3	3	1	3	1	11
(9)	Pneumatic	3	2	3	1	2	11
(10)	Photo & Gas Ion.	3	1	3	3	1	11
(11)	Fusible Electric Insulation	3	3	2	1	1	10
(12)	Electronic Gas	2	3	1	3	1	10
(13)	Submicron Particle	3	3	1	1	2	10
(14)	Ultrasonic	3	2	1	3	1	10
(15)	Microwave (Radar)	3	2	1	3	1	10
(16)	Infrared & Ultraviolet	2	2	1	3	1	9

*Denotes Sensor selected for hardware development.

TABLE 4. RANK COMPARISON OF SPRINKLER ACTUATOR CONCEPTS

		Criteria				Score Legend
						3 = Good 2 = Fair 1 = Poor
Rank	Actuator Type	Reliability	Cost	On-Off Capability	Extra Power or Equipment Requirements	Total Score
(1)	Nitinol	3	3	3	2	11*
(2)	Pyrotechnic	3	2	3	2	10*
(3)	Powered Nitinol	3	3	3	1	10*
(4)	Fusible Link	3	3	1	3	10*
(5)	Frangible Glass Bulk	3	3	1	3	10
(6)	Bimetallic	3	2	3	1	9
(7)	Bellows	3	1	3	2	9
(8)	Solenoid Valve	3	1	3	1	8*

*Denotes Actuator selected for hardware development.

ELECTRONIC FIRE DETECTION BY SENSING THE THERMAL SIGNATURES OF A FIRE

A fire has many properties which make it detectable. These properties or "signatures" have been mentioned previously in the discussion dealing with sensors. The thermal property of a fire is the rapid increase of the room ambient temperature, or an excessively high temperature. Since the temperatures in a residential building rarely display these properties without the presence of a fire, the rapid increase or an excessive ambient temperature can be viewed as the signatures of a fire.

The following is a description of several concepts which could be used to detect a fire by electronic means. Figure 1 shows the basic elements necessary to effect the detection of a fire through its thermal signatures. The system must contain a sensing device which outputs an electrical quantity. This electrical quantity must in some way be related to the ambient temperature. The sensor output is then processed by the electronic circuitry to yield two logical signals. Each of these logical signals can either be TRUE or FALSE. The rate-of-rise (RR) signal is TRUE if, and only if, the ambient temperature increases at a rate greater than some specified rate, normally 0.14 °C/s. The threshold (TH) signal is TRUE if, and only if, the ambient temperature is greater than some specified limit, normally 57 °C. These two logical signals are logically OR-ed in order to yield a single bit of information indicating the presence of a fire. The OR gate output is the FIRE signal, and it is TRUE if either RR is TRUE, or if TH is TRUE, or if both RR and TH are TRUE.

Analog and digital methods were considered in developing the electronic fire detection concepts. The analog concepts considered are listed below:

- UNISENSOR - A single sensor is used to obtain both the RR and the TH signals. The sensor output is related to the absolute ambient temperature.
- BISENSOR - Two nearly identical sensors are used to obtain the RR and TH signals. Both sensors outputs are related to the absoulute ambient temperature.
- DUALSENSOR - Two different sensors are used. One sensor's output, related to the absolute temperature, yields the TH signal. The

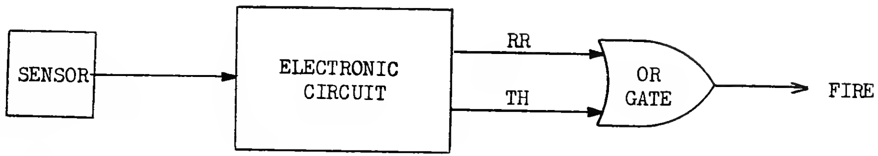

FIGURE 1. BASIC ELECTRIC COMPONENTS TO SENSE THERMAL SIGNATURE

other sensor's output, related to the derivative of temperature, yields the RR signal.

Two digital concepts were considered, and their description follows:

- CONVERTING - This concept is identical to the UNISENSOR approach except that the output of the sensor is converted to a digital word and then processed digitally.
- COUNTING - A sensor which outputs a frequency proportional to temperature is used. A counter is used to obtain the relevant digital data.

Each of the above concepts will be described in block-diagram form. Two of the above, the UNISENSOR and the COUNTING, were implemented and tested.

Unisensor Analog Fire Detector

This electronic approach is capable of supplying the desired one bit of information indicating the presence of a hostile fire. The fire detector will yield a FIRE TRUE signal if either a predetermined absolute temperature threshold is exceeded or if a predetermined rate-of-rise of temperature is exceeded. The block diagram of the fire detector system is shown in Figure 2. The output of the sensor and linearizing network is a voltage (V_1) which is a linear function of the temperature $V_1 = m_1T + b_1$.

The voltage, V_1, is then shifted by a preset amount with the scale center adjustment in order to set the center temperature of the detector operating range. The scaling amplifier, whose output is V_4, sets the end-points of the operating range. The output of the scaling amplifier is (1) compared to the preset temperature threshold and (2) differentiated to obtain the rate-of-rise of temperature data. The differentiator output is then compared to the preset rate-of-rise limit. The output of the comparator networks is either a TRUE or FALSE signal indicating the presence of a fire. These logical signals are inputs to an OR gate which outputs a TRUE signal only if either or both of the comparator outputs are TRUE.

In practice, the direct differentiation of the amplifier output is quite difficult due to the slow rate of change of temperature. This problem was overcome by using the network shown in Figure 3. This network averages

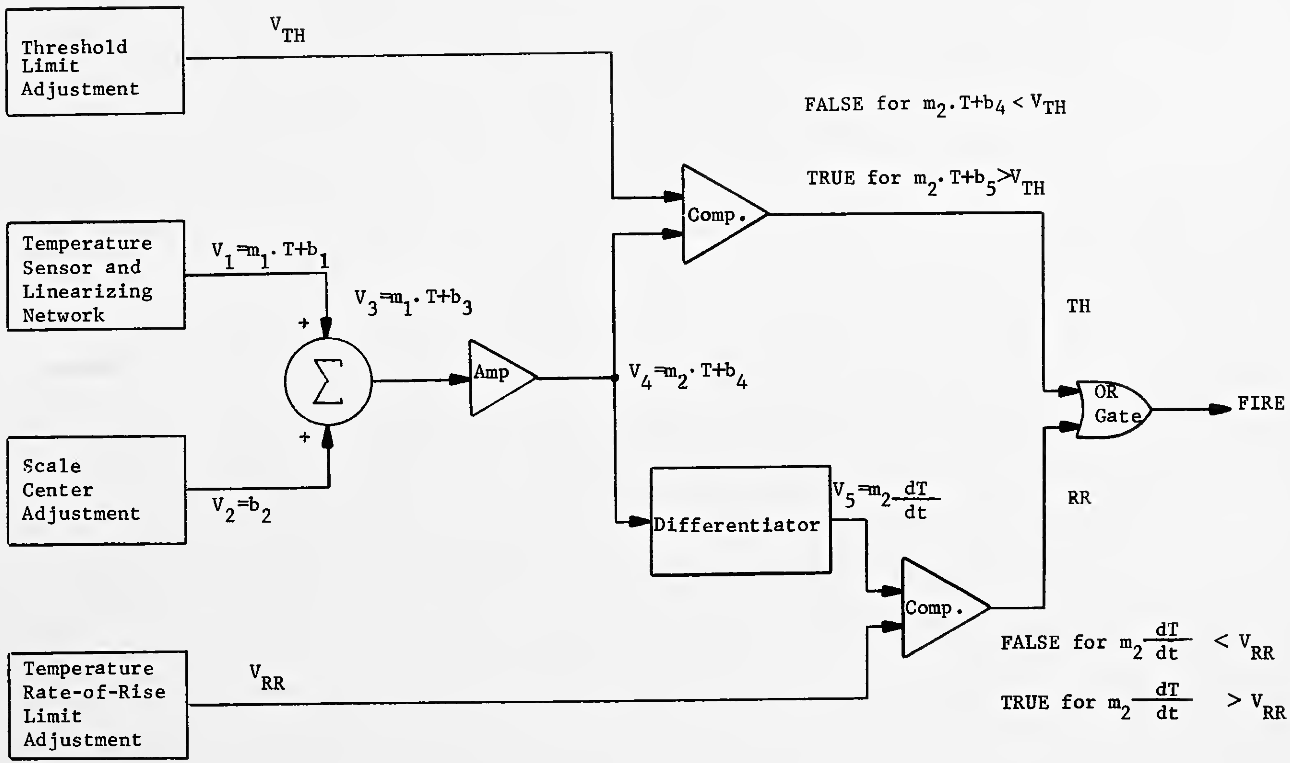

FIGURE 2. THE UNISENSOR ANALOG FIRE DETECTOR

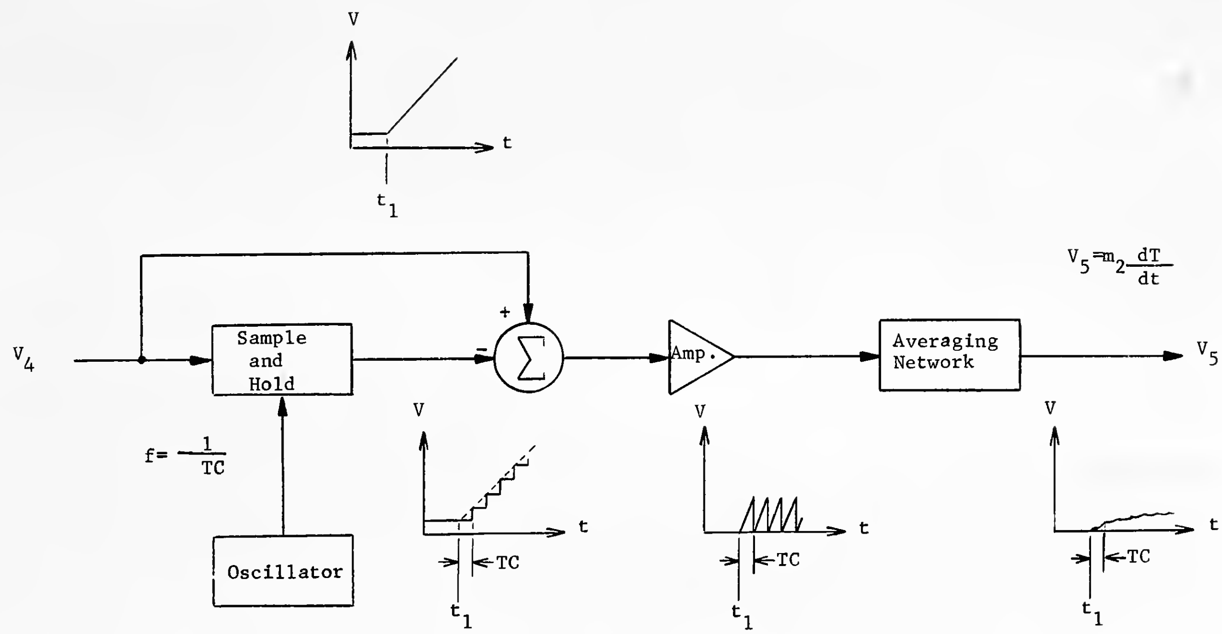

FIGURE 3. PRACTICAL IMPLEMENTATION OF THE DIFFERENTIATOR

over time the difference between the input signal and the sampled value of the input signal. As shown in Appendix A, the output voltage of this network is approximately proportional to the rate-of-rise of temperature.

This sensing concept was implemented using the circuits described in detail in Appendix A. Figure 4 is a photograph of the Unisensor fire detector utilizing a silicon transistor as the sensing element which, for testing purposes, is mounted in a socket on the end of a shielded cable. The banana connectors are used to supply the board with 24 VDC. The detector output is obtained at the terminal post located in the lower left corner of the circuit board.

This concept has several advantages:

(1) Low power consumption (less than 300 mW).

(2) Small thermal mass of sensor resulting in a quick response.

(3) No radioactive components.

(4) No high voltages.

The main drawback of this system, as with all analog systems, is that some of the components must have a very small temperature coefficient in order to assure high accuracy over a wide temperature range. This effect is discussed in the results of the controlled temperature tests.

The component cost for the fire detector was estimated to be $12.59 in single quantities and $7.04 in hundred quantities. Cost of the components are shown in Appendix A.

Bisensor Fire Detector

Figure 5 shows a block diagram of the BISENSOR detector cocept. In this approach, two nearly identical sensors are used. The sensors differ only in their thermal time constants. The TH signal is obtained by processing the output of sensor #1. This processing is identical with that used in the UNISENSOR detector. The RR signal is obtained by amplifying the difference between the outputs of the two sensors and comparing the amplified signal to a rate-of-rise limit, since the difference between the outputs of two sensors, having unequal thermal time constants, in the steady state is proportional to the derivative of temperature. The FIRE signal is again obtained by OR-ing RR and TH.

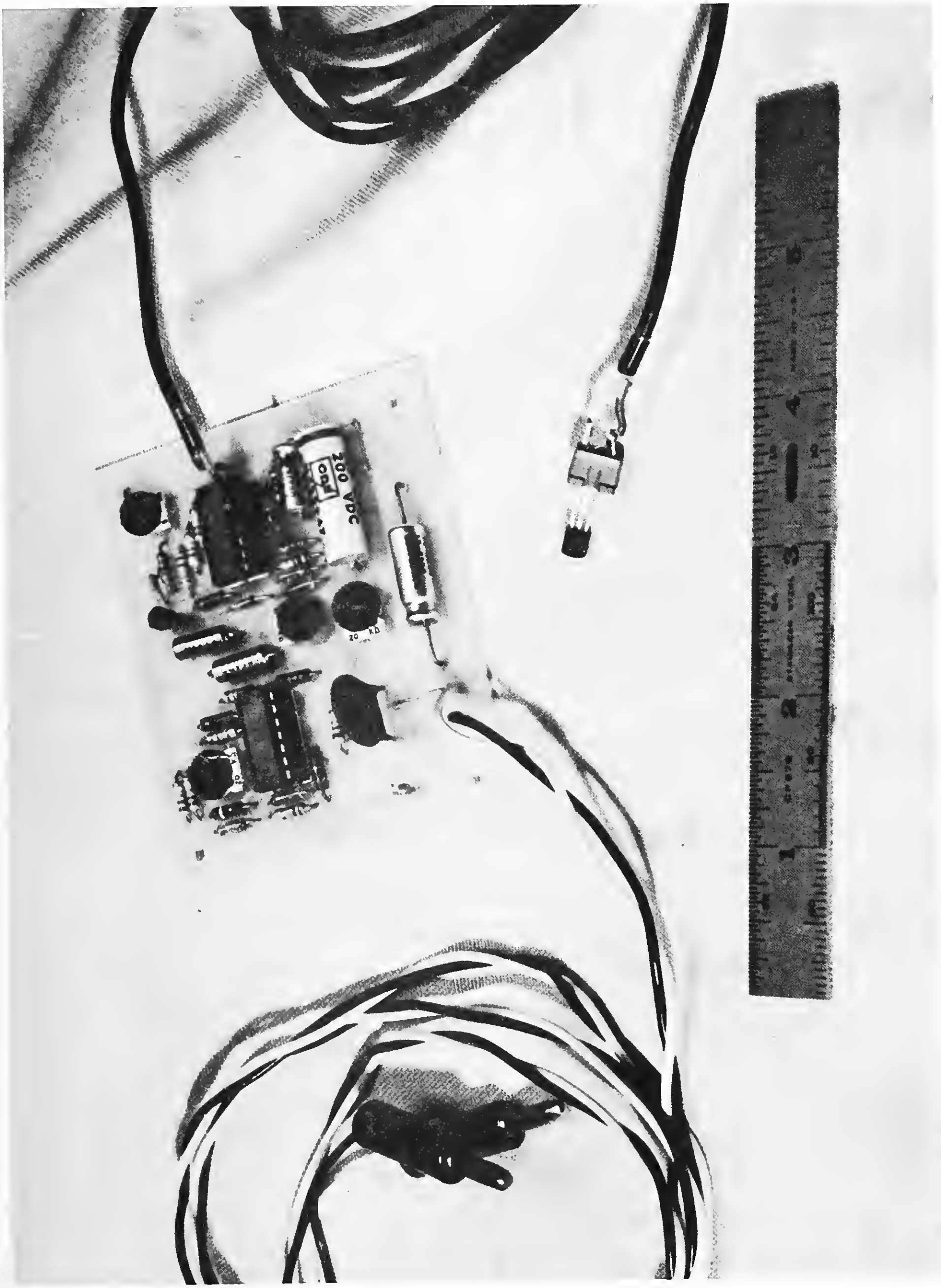

FIGURE 4. THE UNISENSOR ANALOG FIRE DETECTOR

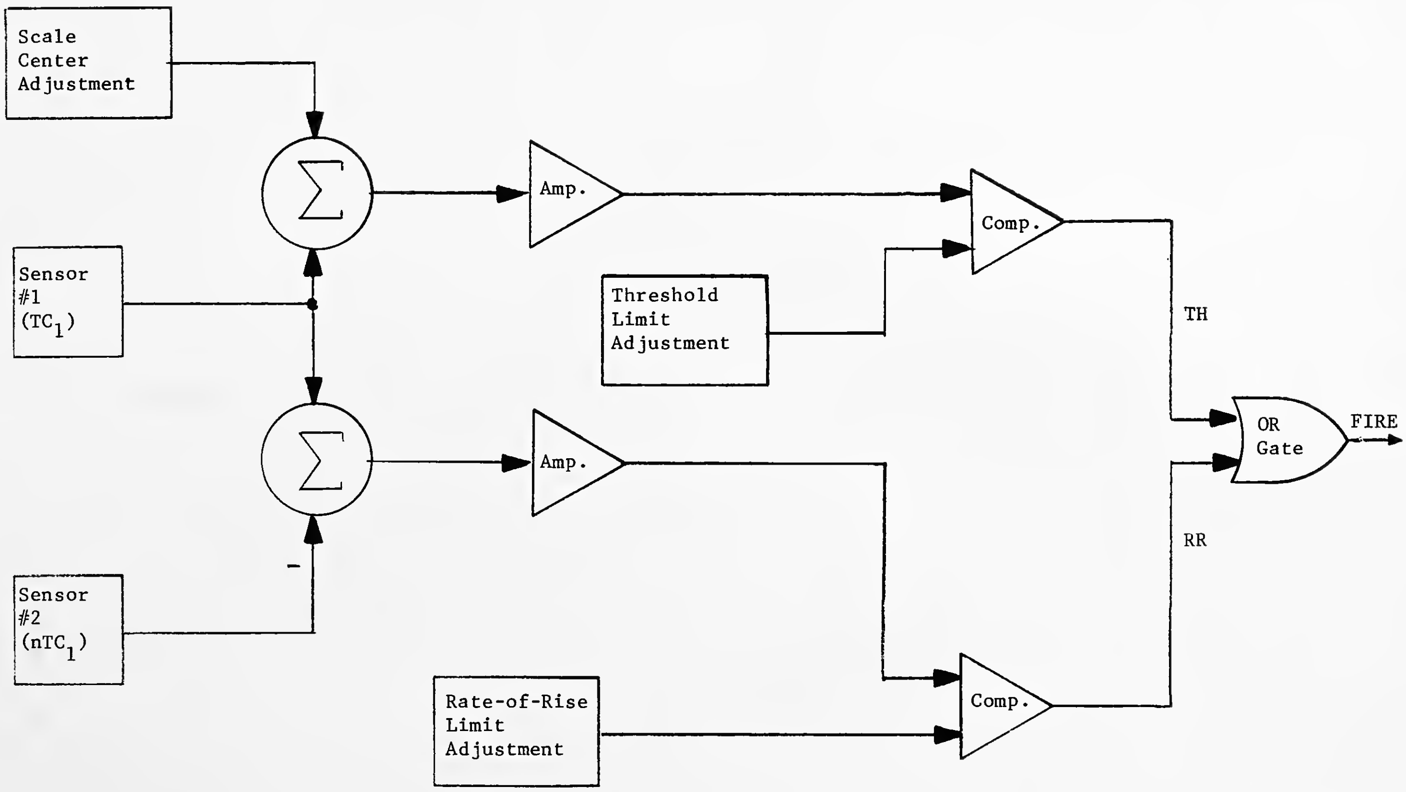

FIGURE 5. BISENSOR FIRE DETECTOR

The BISENSOR approach results in a much simpler circuit than the UNISENSOR concept. Since the differentiation is effected through subtraction of two signals, neither of which is delayed in time, the oscillator and sample-and-hold circuits are not required. In the UNISENSOR method, these two circuits are the most likely sources of error.

Dualsensor Fire Detector

The block diagram of the DUALSENSOR detector is shown in Figure 6. In this concept, two separate sensors are used to obtain the RR and TH signals. An absolute temperature is used to obtain the TH signal, utilizing identical processing as in the UNISENSOR approach. The RR signal is obtained by processing the output of a sensor which provides data proportional to the derivative of temperature. An example of such a sensor is the piezoelectric polymer distributed by the Pennwalt Corporation. The processing of this sensor's output is identical with that used to obtain the TH signal.

Converting Fire Detector

Figure 7 shows the block diagram of the CONVERTING digital detector. In this approach, the output of the absolute temperature sensor is converted to a binary word by an analog-to-digital converter (A/D). The output of the A/D is compared to a threshold limit by a digital comparator to yield the TH signal. Also, A/D output is differentiated by subtracting the current binary word from a previous word which was saved in the latch. The subtractor output is proportional to the rate-of-rise of temperature, and by comparing it to a preset limit, the RR signal is obtained. In order to maintain high accuracy in the differentiation, the process must be controlled by a very stable clock. Once again, the FIRE signal is obtained by OR-ing TH with RR.

Counting Fire Detector

The sensing element in the COUNTING digital fire detector, shown in Figure 8, is the temperature-to-frequency converter (T/F). The output of

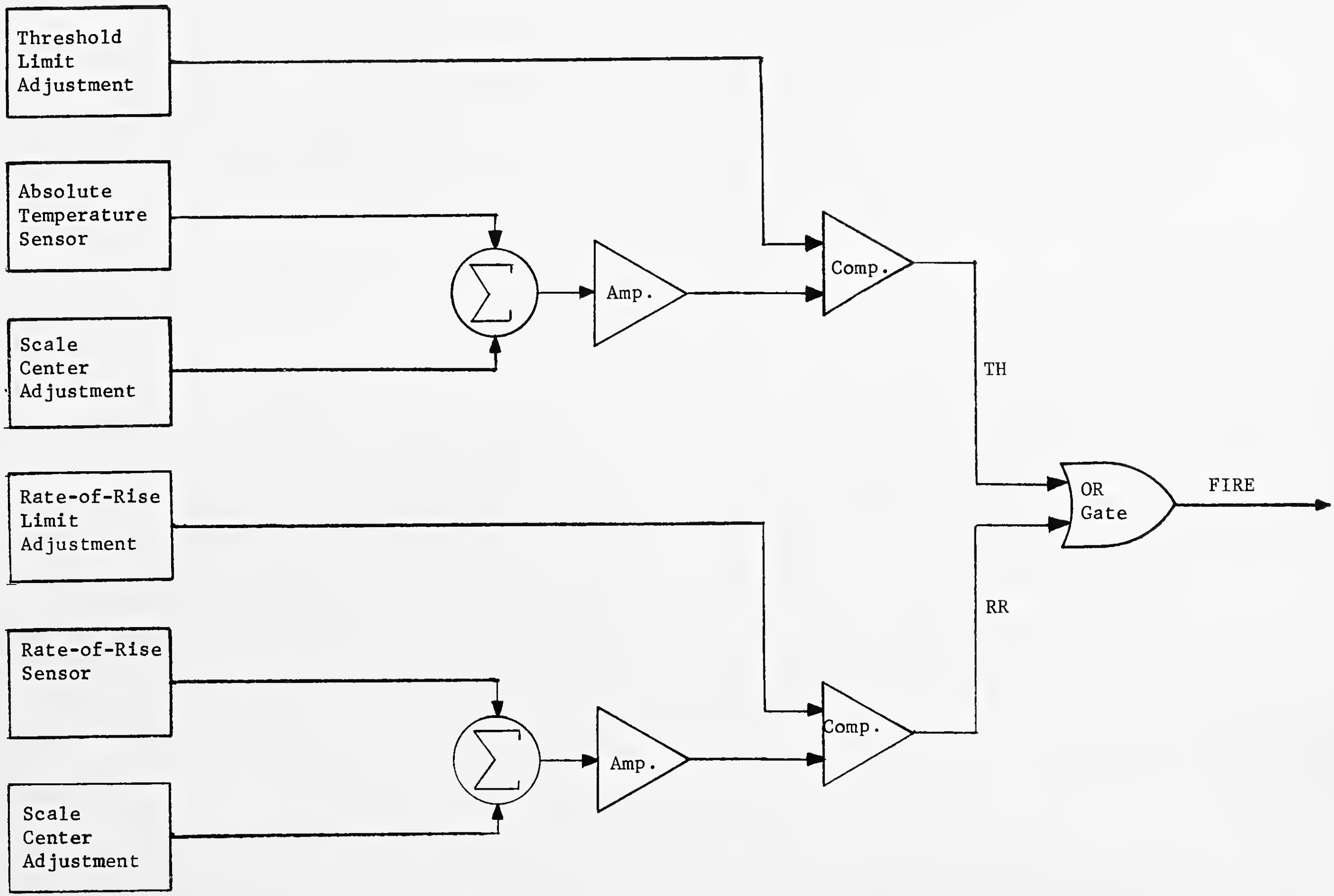

FIGURE 6. DUALSENSOR FIRE DETECTOR

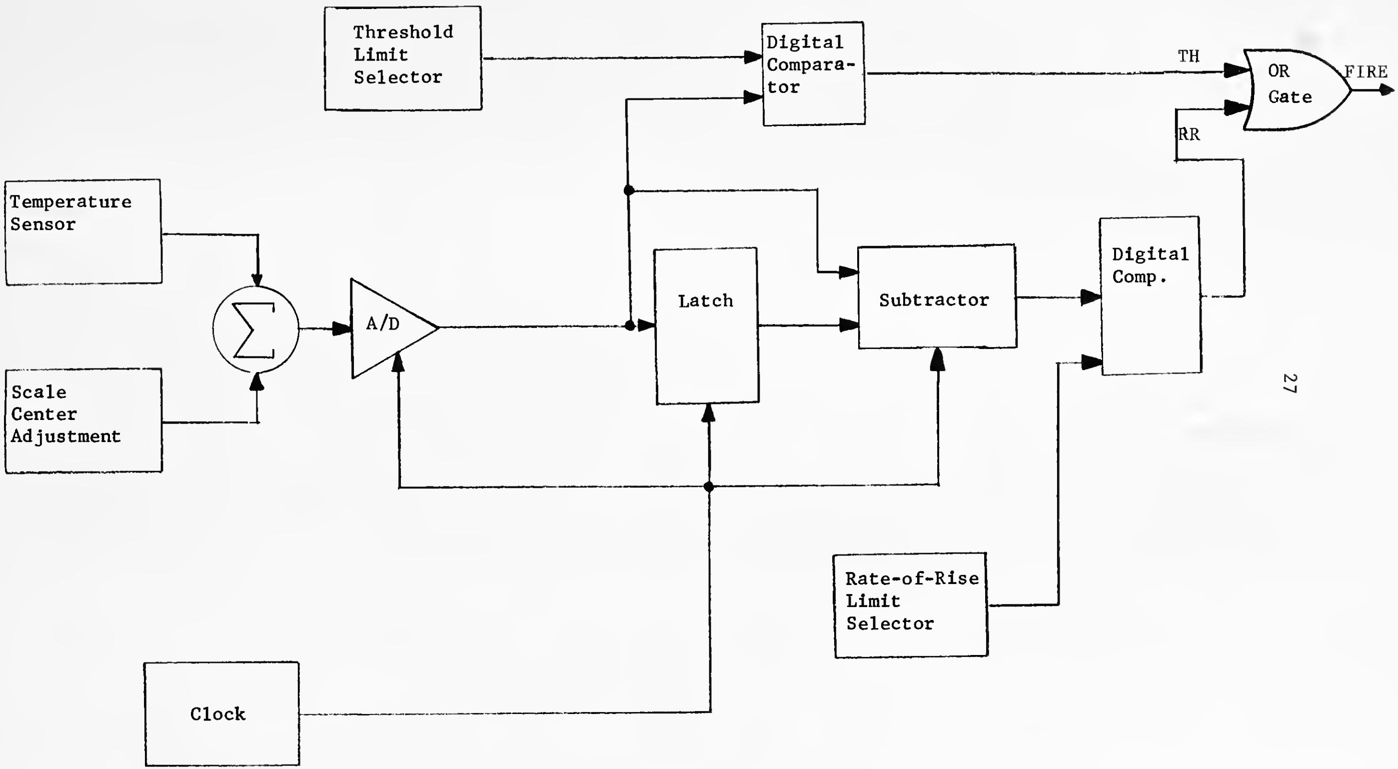

FIGURE 7. CONVERTING FIRE DETECTOR

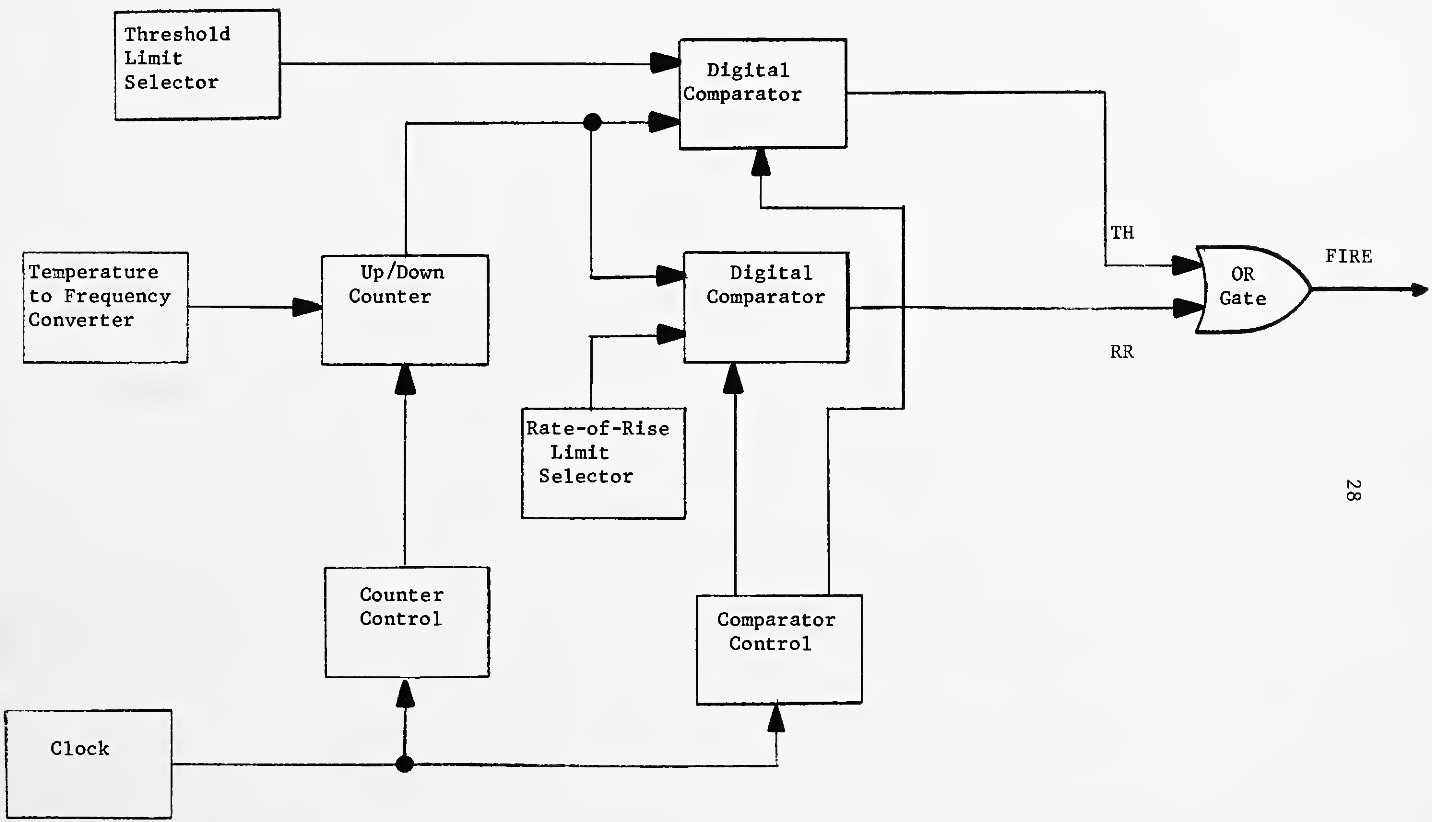

FIGURE 8. COUNTING FIRE DETECTOR

the T/F provides the clock input of an up/down counter (U/D). The processing of the T/F output consists of six discrete operations which are timed by a very stable clock. The six operations are listed and described below:

(1) Parallel Load - The U/D is initialized by parallel loading a zero into the count register.

(2) Count Up - The U/D counts up at the rate of the T/F output.

(3) Compare Count 1 - The terminal count in the counter register is compared to a selected value to yield the TH signal.

(4) Count Down - The U/D counts down, starting with the terminal count, at the rate of the T/F output. The resulting count represents the difference between the count up and count down frequencies (i.e., temperatures) and is proportional to the derivative of temperature.

(5) Compare Count 2 - The difference count is compared to a selected value to yield the RR signal.

(6) Reinitialize - The digital system is reinitialized so that the process can repeat.

Once again, TH is OR-ed with RR to yield the FIRE signal. The U/D counter modes are selected by the counter control network, and the digital comparators are activated by the comparator control network. Both of the control circuits are synchronized with the system clock.

This sensing concept was also implemented using the circuits described in detail in Appendix C. The model, as shown, functioned repeatedly in laboratory tests for both a threshold and a rate-of-rise limit violation.

This concept shows great promise for this application due to the inherent stability of digital circuits. All of the processing circuitry could be implemented on a single integrated circuit, minimizing both size and cost.

BATTELLE CONCEPT MODELS

Solenoid Valve Actuator

The block diagram of an electronic detector and solenoid actuator system is shown in Figure 9. Component details are included in Appendix C. The solenoid actuator consists of a detector-to-solenoid interface and a solenoid valve. At the interface, a noise filtering network is used to prevent false actuation. The filtered FIRE signal is input to a timing circuit, which in turn controls the solenoid driver network. If FIRE is TRUE, the solenoid driver is active. The solenoid driver is then deactivated following a preset time delay after the FIRE signal goes FALSE. The time delay is present to assure complete dousing of the fire. This device and the following models were built and tested at Battelle. The subsequent chapter on "Testing" includes laboratory data. The cost of components for the solenoid valve actuator is $4.57 and $2.22 in single and hundred quantities, respectively. The cost of a commercial solenoid valve is about $30 each in large quantities. These costs are near the upper limit for typical homeowner budgets. The next electric actuator described offers components having a reduced total cost.

On-Off Pyrotechnic Actuator

A block diagram of the pyrotechnic actuator is shown in Figure 10. For greatest noise immunity and minimal wiring costs, the electronic components of the interface should be located on the same board as the detector. At the interface, a noise filtering network is used to eliminate the possibility of erroneous actuation. The filtered FIRE signal is then input to a timing network. If FIRE is TRUE, the ON pulse generator is activated, and the sprinkler is turned on. The transition of the FIRE signal from TRUE to FALSE activates the timing circuit which delays the actuation of the OFF pulse generator circuit by a preset amount of time. The time delay must be sufficiently long to assure the dousing of the fire. Multiplexing the ON and OFF commands onto a twisted-pair cable reduces the interconnecting costs, and a demultiplexer, located at the sprinkler head, separates the two commands.

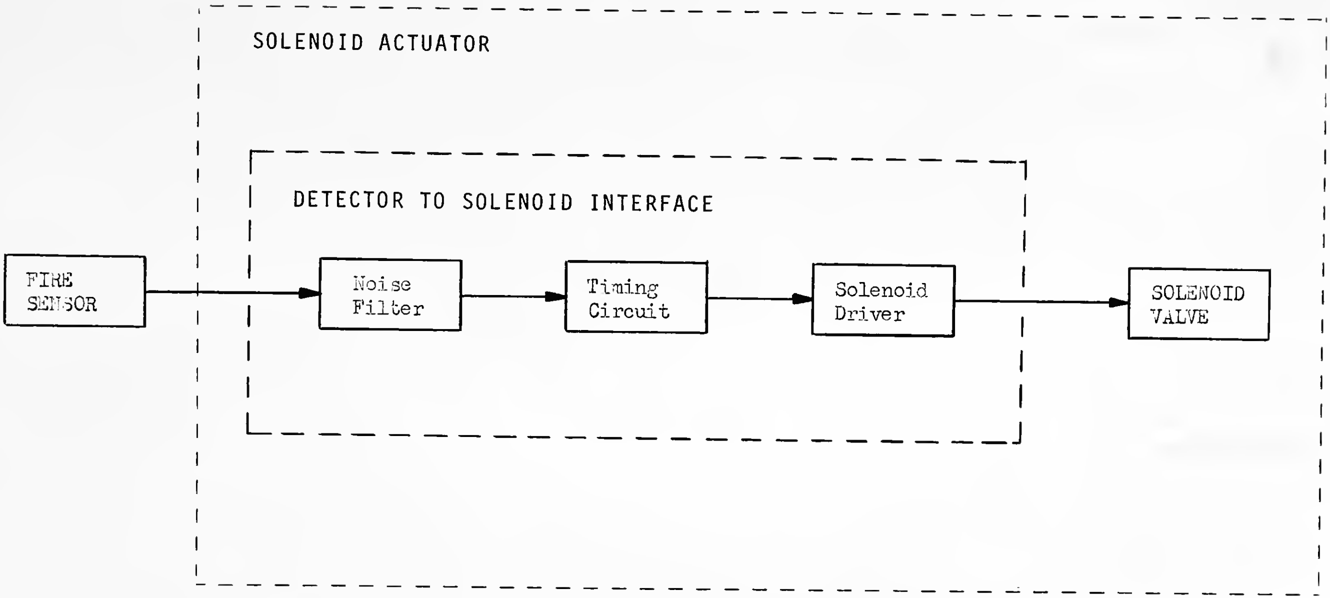

FIGURE 9. THE SOLENOID VALVE ACTUATOR

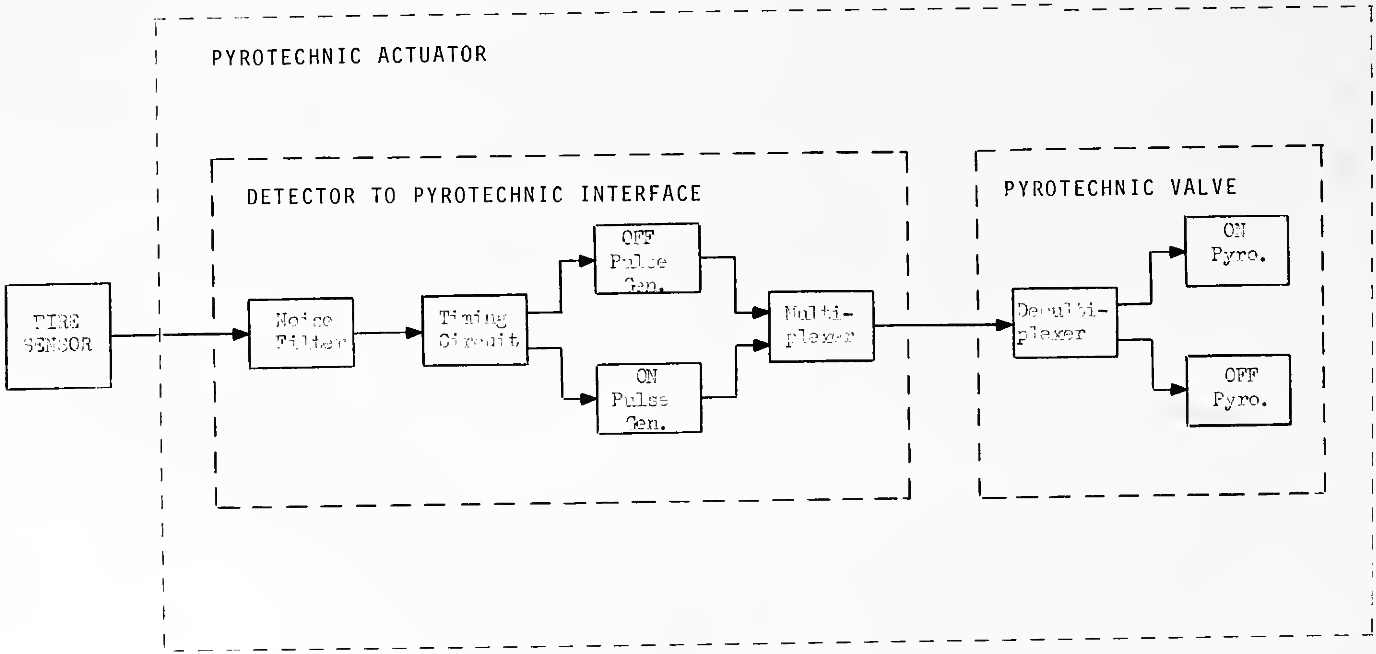

FIGURE 10. THE PYROTECHNIC ACTUATOR

Since the pyrotechnic actuator requires two separate pulses, the circuit complexity is increased over that which would have been necessary for the solenoid actuator. The cost of the components for the interface board is \$12.59 and \$7.04 in single and hundred quantities, respectively. The cost of the pyrotechnic devices themselves, however, can be as low as \$8 for both squibs used in the Battelle valve. An exploded view of the valve is shown in Figure 11.

Modified Fusible Link Sprinkler

This was Battelle's first all-mechanical attempt to improve the thermal response time of conventional fusible link sprinklers. Shown in Figure 12 is a photograph comparison of a conventional industrial fusible link sprinkler (left side of photograph) with the modified sprinkler (right side of photograph).

The modified sprinkler is almost identical to the conventional unit, except it has a different link and linkage arms, which are visible in the photograph. Also, the modified sprinkler has an internal 1/4-inch diameter flow restrictor while the industrial orifice is 1/2-inch diameter. The smaller orifice, which is more suited to residential fires, requires less force to seal at a given pressure. This effect, combined with a linkage that offers a higher lever ratio, allows the designer to utilize a weaker, and therefore thinner and more sensitive, fusible link.

The novel fusible link is made by Falcon Safety Products, Inc. of Mountainside, New Jersey. It is normally used to actuate a freon powered sonic fire alarm by releasing a spring which opens a valve. It consists of two stainless steel sheets bonded by a 136^{o}F eutectic solder. Each sheet is 30 gage, cut 1 x 2 cm with a small eye along one of the longer edges. The plates are configured parallel, with the eyes of each plate opposite to each other to form a link. The link is attached by its eyes to the sprinkler linkage arms in the same fashion as a conventional link.

Notice the significant increase in surface area-to-volume ratio of the Falcon link in the photograph compared with the conventional link. While the surface area of the Falcon may be only about 1/3 that of the conventional (which means it may receive only 1/3 the heat input), the Falcon is 10 times

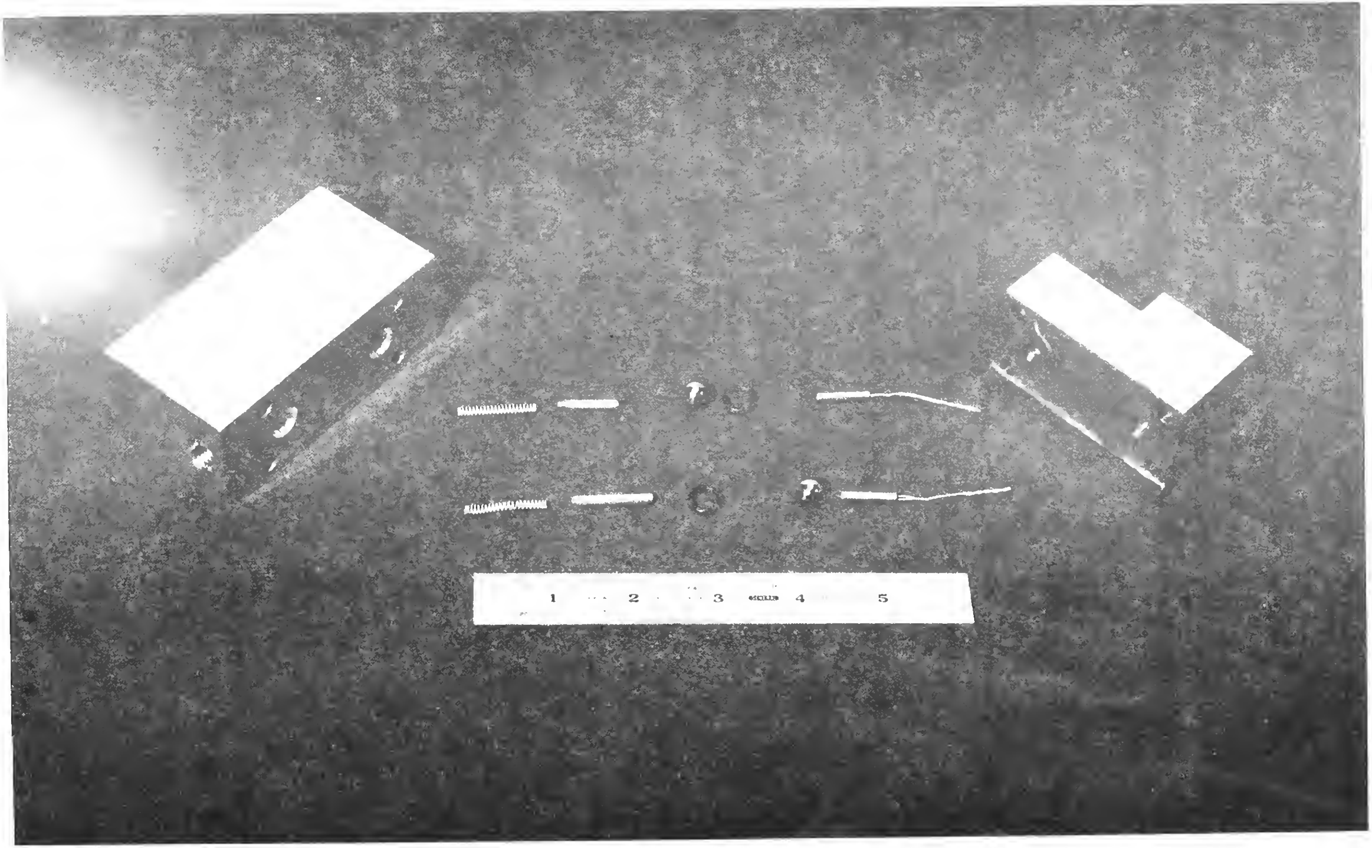

FIGURE 11. EXPLODED VIEW OF ON-OFF PYROTECHNIC VALVE

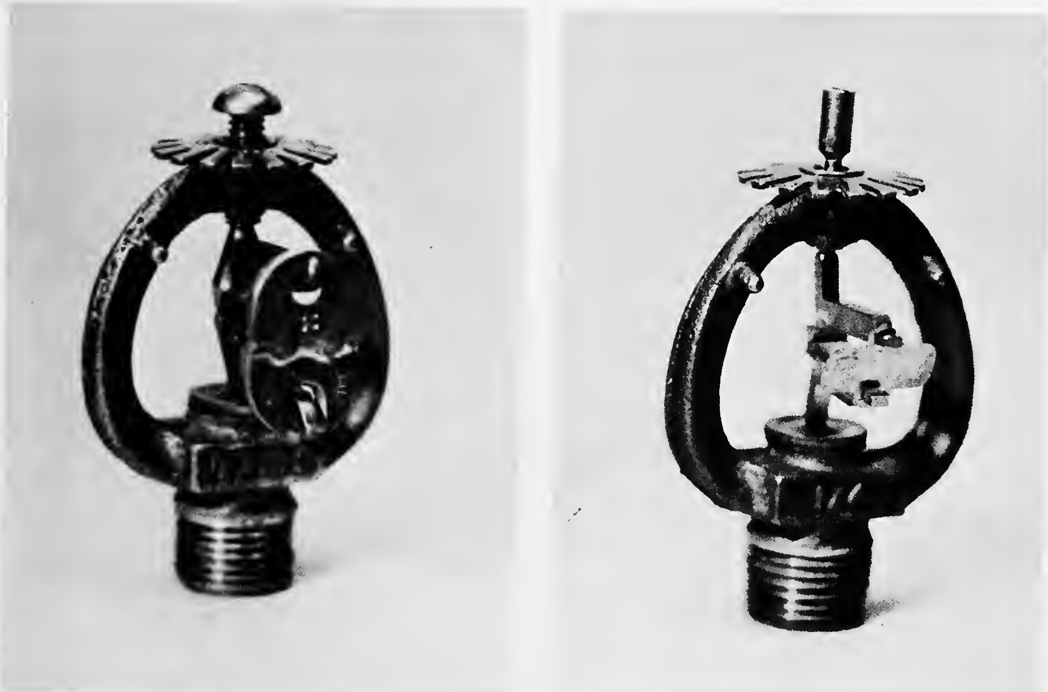

FIGURE 12. CONVENTIONAL AND MODIFIED FUSIBLE LINK SPRINKLERS

thinner and, therefore, can conduct heat faster, with the net effect being a more thermally responsive sprinkler. The Falcon sprinkler performed well in the temperature response and water flow tests discussed in the next section; however, it did not fare well in the hydrostatic leakage tests.

Nitinol Link Sprinkler

The Nitinol link sprinkler, shown in Figure 13, was designed to have a fast thermal response by employing a small piece of Nitinol with a high surface area-to-volume ratio. Nitinol wire 0.049 in. dia. x 5 in. long was selected. Such a piece of wire is capable of being stretched with 150 pounds tension to 5.35 inches long. The stretched wire was placed into a fixture that connects one end of the wire to a strut that is designed to withstand a hydrostatic leakage test on the sprinkler up to 875 psi. The other end is connected to the fixture, which results in the wire pulling out the strut when the Nitinol is heated and contracts.

In testing, this device has substantially increased thermal response and sustained a hydrostatic test of 875 psi without leakage. It is based on a conventional 1/4-inch sprinkler and, therefore, has good waterflow characteristics. The model in the photograph can be modified in appearance to be more eye appealing and still retain low cost and high performance. Convective and conductive heat transfer calculations to theoretically determine Nitinol wire thermal response times indicate potential performance comparable to or better than accepted minimum response parameter of Tau = 21. This was borne out in subsequent testing described in this report (see page 47).

Nitinol On-Off Sensor Actuator

This model further employs the usefulness of Nitinol to automatically turn water flow off after the Nitinol wire sensor returns in temperature below the threshold response level. This is accomplished by spring loading the Nitinol. Thus, a sprinkler could start a small flow at 135°F and produce a progressively larger flow up to a maximum at 150°F. After the waterflow extinguishes the fire back below 150°F, the sprinkler progressively shuts off until 135°F sensor temperature is reached and the waterflow is stopped. In

FIGURE 13. NITINOL LINK SPRINKLER

the unlikely event a fire returns after waterflow stops, the reusable Nitinol will actuate water flow again once the sensor is heated above the predetermined temperature level.

The Nitinol effect is caused by recrystallization of the nickel and titanium molecules between two solid states. This occurs in a temperature range set by the weight ratio and processing of nickel and titanium. This range can be made as small as 15°F. As previous research has demonstrated the usefulness of a 135°F temperature threshold limit for residential bedrooms, living rooms, and kitchens, Battelle designed the 0.049 dia. x 1 inch sensor of the on-off actuator to have a temperature transformation rage of 135°-150°F.

In Figure 14, Battelle spring-loaded a lever that actuates a push-button valve. The lever pin and positioning screw are mounted in a frame which is attached to the valve body. The Nitinol sensor is placed between the valve body and the lever, with the lever fully depressing the spring at room temperature. This is done by screwing down the positioning screw. After the Nitinol ends are fastened, the screw is unthreaded, allowing the spring to force the lever back which closes the valve and streches the Nitinol. The device is then ready for operation. When heated from 135°F to 150°F, the Nitinol contracts 0.020 inch and pulls the lever down, thereby actuating the valve. In doing so, the Nitinol exerts a 50-lb. compressive force. After the fire is extinguished and the sensor temperature falls below 135°F, the spring can force the Nitinol to once again stretch and close the valve.

The Battelle model shown in the photograph is only a proof-of-principle device. It was built with Nitinol possessing a temperature transformation range of 100° - 125°F, a steel linkage, and a low water-flow aluminum and brass valve. Overall, the thermal response of the Nitinol on-off sensor actuator is very fast; however, the first model has low flow and hydrostatic leakage capabilities. The performance could be increased significantly by redesign and construction of most parts with temperature resistant, high-strength plastic. This would result in a sprinkler head of significantly reduced cost as well as increased simplicity and visual appearance. Although the off feature may be desirable, it does add complexity and cost to this model in comparison with the simpler on-only Nitinol sprinkler previosly shown in Figure 13.

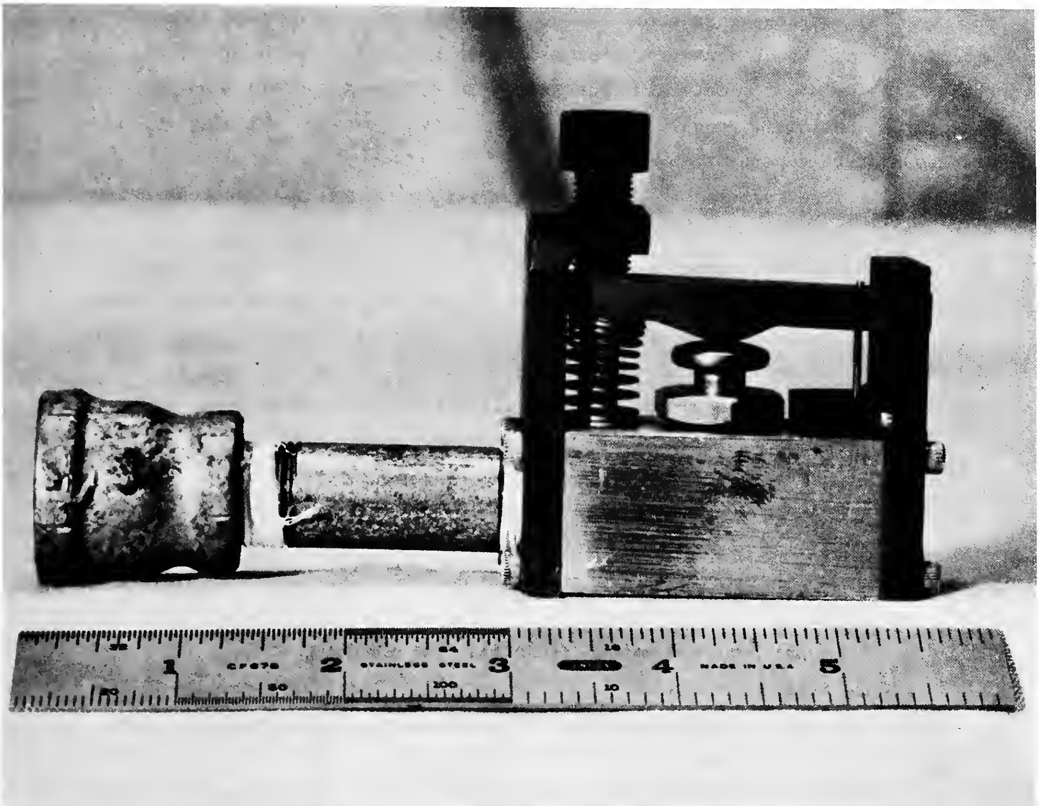

FIGURE 14. NITINOL ON-OFF SENSOR ACTUATOR

LABORATORY PERFORMANCE OF BATTELLE CONCEPT MODELS

Controlled Temperature Tests

The response characteristics of the unisensor analog fire detector were determined under varied environmental temperatures. The purposes of these tests were: (1) determine the effect of ambient temperature on the detector's sensitivity and (2) gain insight into the system variables which are temperature dependent.

The test system configuration is shown in Figure 15. The test equipment used is listed and described below:

(1) Duffers Associates "Gleeble" - A device which controls the time/temperature profile of a conductive specimen; in this case, a small piece of aluminum. The desired time/temperature profile is "programmed" via a front panel.

(2) Refrigerator/Oven - A controlled temperature environment for the detector circuit board. This device was implemented by using an incubator oven. To obtain temperatures below room temperature, alcohol was circulated through copper tubing between a container filled with dry ice and the incubator.

(3) Remote sensing thermometer - A device to display the detector circuit board temperature. A Simpson 260 with the 652 thermocouple adaptor was used for this function.

(4) Strip Chart Recorder - A Honeywell 194 dual pen recorder was used to obtain a plot of the specimen temperature and the logical FIRE detector output signal.

(5) Low-Pass Filter - In order to reduce the electrical noise generated by the "Gleeble," a second-order Butterworth filter was inserted into the detector circuit immediately following the sensor buffer. The filter network was maintained at room temperature.

(6) Power Supply - A 24 VDC supply supplied the power to the detector circuitry and the low-pass filter.

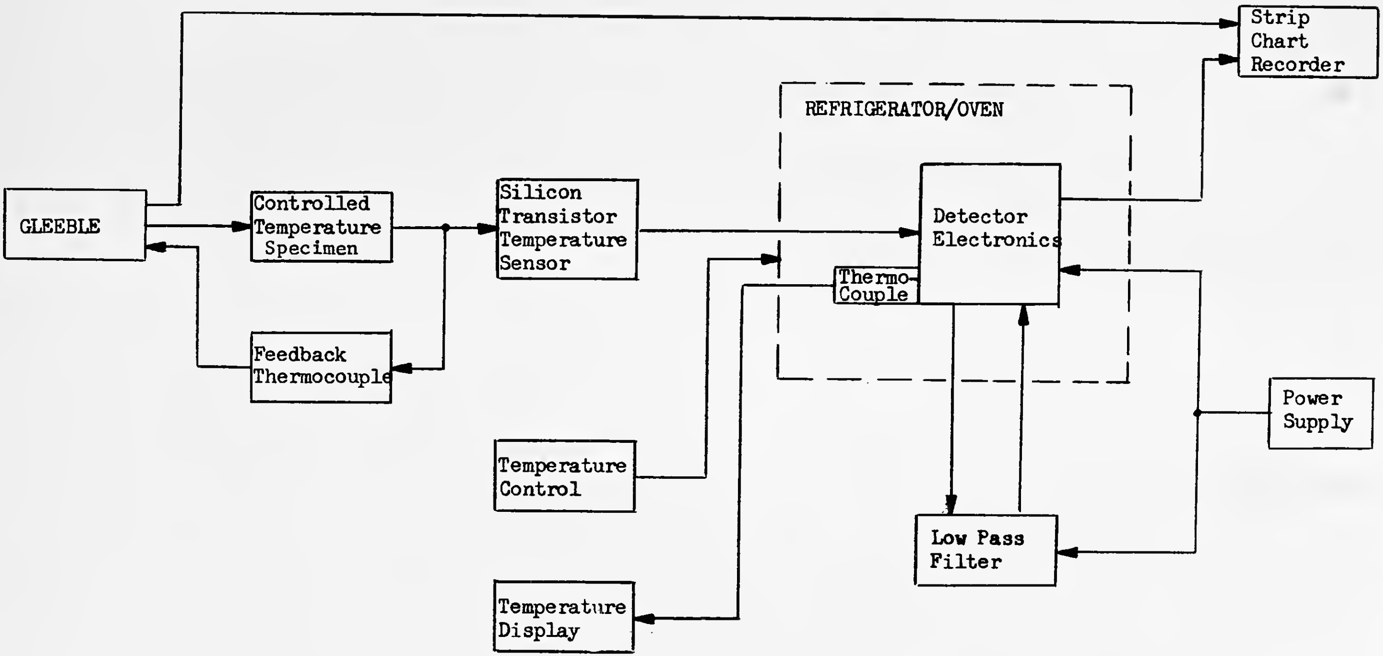

FIGURE 15. SYSTEM CONFIGURATION FOR CONTROLLED TEMPERATURE TESTS

The "Gleeble" was used to increase the temperature of the specimen from approximately 25°C at a programmed rate. The sensor was thermally coupled to the specimen, and therefore tracked the specimen temperature. In effect, the "Gleeble" provided the termperature forcing function for the sensor. The forcing functions used in these tests were ramps with slopes as listed below:

(1) $dT/dt = 0.23^{\circ}C/sec.$ ($24.8^{\circ}F/min.$)

(2) $dT/dt = 0.19^{\circ}C/sec.$ ($20.5^{\circ}F/min.$)

(3) $dT/dt = 0.16^{\circ}C/sec.$ ($17.3^{\circ}F/min.$)

(4) $dT/dt = 0.14^{\circ}C/sec.$ ($15.0^{\circ}F/min.$)

(5) $dT/dt = 0.12^{\circ}C/sec.$ ($13.0^{\circ}F/min.$)

(6) $dT/dt = 0.09^{\circ}C/sec.$ ($9.7^{\circ}F/min.$)

(7) $dT/dt = 0.05^{\circ}C/sec.$ ($5.4^{\circ}F/min.$)

Several of the above temperature forcing functions were input to the sensor while the detector circuit board was maintained at each of the following temperatures.

(1) $T_a = 0^{\circ}C$ ($32^{\circ}F$)

(2) $T_a = 10^{\circ}C$ ($50^{\circ}F$)

(3) $T_a = 20^{\circ}C$ ($68^{\circ}F$)

(4) $T_a = 23^{\circ}C$ ($73.9^{\circ}F$)

(5) $T_a = 25^{\circ}C$ ($77^{\circ}F$)

(6) $T_a = 30^{\circ}C$ ($86^{\circ}F$)

(7) $T_a = 40^{\circ}C$ ($104^{\circ}F$).

Each time the ambient temperature was changed, the test was delayed for ten minutes so that the components on the circuit board could attain the ambient temperature. Throughout the test, the circuit board ambient temperature was continuously monitored. The test output consisted of a strip chart recording of the temperature forcing function and the logical FIRE variable from the detector.

Table 5 shows the response time of the detector for the various input forcing functions and ambient temperatures. Those response times followed by a (*) indicate that the FIRE signal was TRUE due to the rate-of-rise circuitry. Figure 16 shows a plot of the threshold response sensitivity as a function of temperature, and the rate-of-rise sensitivity is plotted in

TABLE 5. DETECTOR RESPONSE TIME

(°C/sec.)	t_r (sec.)						
dT/dt	0°C(32°F)	10°C(50°F)	20°C(68°F)	23°C(73.4°F)	25°C(77°F)	30°C(86°F)	40°C(86°F)
0.23	170	160	70*	50*	50*	60*	110
0.19	-	170	160	50*	70*	110*	120
0.16	230	-	210	110*	140*	170	-
0.14	260	250	-	90*	200	200	170
0.12	330	-	-	250	230	220	190
0.09	390	350	-	330	280	240	-
0.05	680	-	-	-	430	480	-

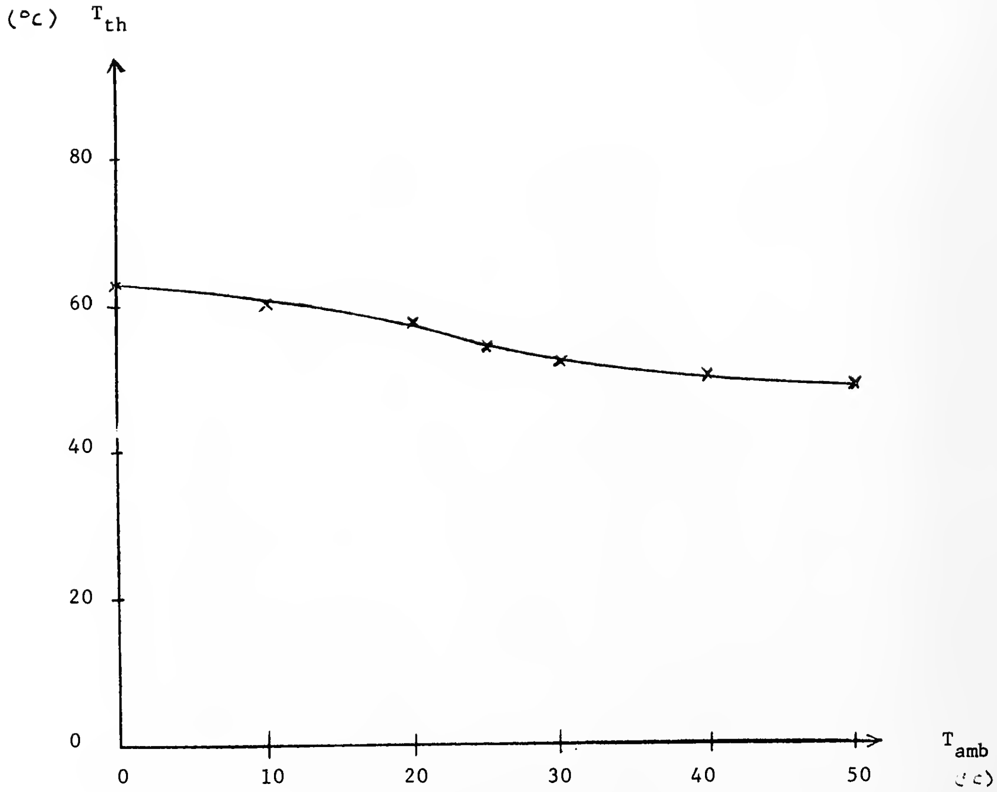

FIGURE 16. THRESHOLD SENSITIVITY AS A FUNCTION OF TEMPERATURE

Figure 17. The rate-of-rise of temperature sensitivity was the lowest dT/dt that would produce a TRUE signal from the detector prior to reaching the threshold temperature.

Temperature Response Tests

The purpose of this test is to measure the thermal response lag existent in a given sprinkler or sensor under the conditions of a typical residential fire immediately prior to flashover. (These conditions, about one to six inches below the center ceiling of a typical room, have been determined by the Factory Mutual Research Corporation to be approximately 275°F turbulent air blowing at 5 ft./sec. Battelle built a facility to simulate these conditions.) In the test, a sprinkler is plunged from standard conditions (room temperature) into the test atmosphere. The time from "plunge" to sprinkler activation provides the quantitative measurement of response time. "Plunge Test" was originally developed at Factory Mutual Research Corporation.

The Battelle plunge tester consisted of a hot-air blower connected to a 4-inch diameter duct, 24 inches long. The blower heater element and fan were separately controlled to produce 5 ft./sec. and 275°F at the center outlet of the duct, 2 inches away from the duct. A hinged, steel frame was used to contain a water-pressurized sprinkler at room temperature away from the hot-air outlet. The hinge is designed to allow the sprinkler to be quickly moved into the air stream so a time measurement can be made.

Battelle compared commercially available sprinklers with the concept models using the plunge tester. Test data follows in Table 6.

Water Flow Tests

The purpose of the water flow tests is to measure the relative flow capabilities of a given sprinkler or actuation valve. By supplying water at 10 to 100 psi, measuring flow rates in gpm, and determining pressure drops across each valve, Battelle determined a valve coefficient for each sprinkler/actuator. The valve coefficient, equal to gpm/(psi drop)-1/2, is fairly constant throughout the operating pressure range of sprinklers and is, therefore, a useful comparison tool. Below is a table of experimentally determined

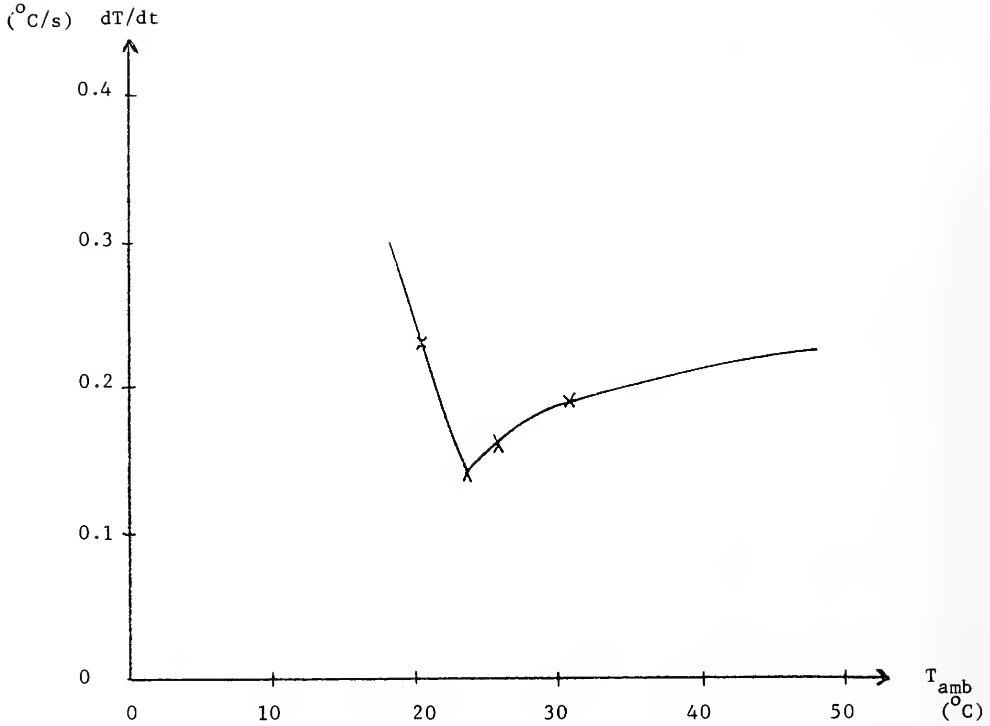

FIGURE 17. RATE-OF-RISE SENSITIVITY AS A FUNCTION OF TEMPERATURE

TABLE 6. PLUNGE TEST DATA

Sprinkler/Sensor Type	Velocity ft./sec.	Temperature °F	Response Time Second
Viking 160° Fusible Link	5	276	53
Grinnell On-Off Aquamatic	5	275	52
Viking 135° Glass Blub	5	281	45
Grinnell 165° Duraspeed	5	275	42
Grinnell 165° Duraspeed	5	275	32
Nitinol Link	5	275	19*
Grinnell Residential Sprinkler Prototype	5	276	6.2**
Grinnell Quck Response	5	278	6
Nitinol On-Off	5	275	5*
Falcon Modified Fusible	5	281	3
Unisensor	5	275	Less than 1

*The Nitinol Link Model was built using a Nitinol temperature transformation range of 180 to 220°F, and the Nitinol On-Off was built using a range of 100 to 125°F. The net effect is that if both models were built with 135 to 150°F Nitinol, the link model would be significantly faster and the on-off slightly slower than the measured Response Time of the concept models.

**Denotes Response Time of Tau = 21 sprinkler.

"valve coefficients" for commercially available sprinklers and the Battelle actuator models. These tests were conducted with a 5/8-inch diameter supply inlet and the valve coefficient calculations were corrected for the velocity head component of pressure drop.

TABLE 7. RESULTS OF WATER FLOW TESTS

Sprinkler/Actuator	Valve Coefficient
Grinnell On-Off Aquamatic	6.9
Grinnell Quick Response	5.8
Viking 1/2 in. Fusible Link	5.7
Grinnell Residential Sprinkler Prototype	3.1
Skinner Solenoid Electric Valve No. 12DA3150	2.6
Viking 1/4 in. Glass Blub	1.6
Nitinol Link	1.4
Viking 1/4, Fusible Link	1.4
Falcon Modified Fusible	1.4
Pyrotechnic	0.56
Nitinol On-Off	0.24

Hydrostatic Leakage Tests

The purpose of these tests is to measure the pressure capabilities of a given sprinkler or actuation valve. Commercially available sprinklers and the experimental actuation valves were progressively pressurized up to 875 psi, and leakage pressure (if any) or other circumstances were noted. This is an extreme test of sprinkler reliability in that pressure levels of 875 psi are rarely encountered in residential water systems. Normal residential operating pressures are 1/10 or less the hydrostatic test pressure. This test does not account for pressure cycles, nor is it intended to be a judge of overall reliability; the test represents an indication of the load-bearing capabilities of sprinkler valve components. Test results are presented in Table 8.

TABLE 8. RESULTS OF HYDROSTATIC LEAKAGE TESTS

Sprinkler/Actuator	Maximum Sealing Pressure, psi
Nitinol Link	875
Pyrotechnic	875
Viking 1/2" Fusible Link	875
Viking 1/4" Fusible Link	875
Grinnell Residential Sprinkler Prototype	875
Grinnell "On-Off" Aquamatic	700
Solenoid	350
Nitinol On-Off	100
Falcon Modified Fusible	100

CONCLUSIONS

(1) Nitinol can be used to perform comparably with the best commercial sprinklers in thermal response, water flow, and hydrostatic sealing tests. Nitinol is relatively inexpensive, corrosion resistant, and stronger than most steels.

(2) Electronic components, specifically the unisensor analog fire detector, can be used to quickly and reliably measure temperature. It consists of relatively inexpensive parts and can decide if temperature levels or temperature rate-of-rise is exceeding preset thresholds and trigger a power supply interfaced with a solenoid or pyrotechnic actuated water valve.

(3) Nitinol can be used to turn water valves off after temperature falls below a preset level; however, this feature increases cost and reduces water flow capabilities.

(4) Electronic components can be used to turn water valves off after temperature falls below a preset valve; however, a less expensive and more practical method of accomplishing this is to trigger an actuator at a delayed time after the temperature falls below the preset valve.

(5) Solenoid actuators have high water-flow capabilities, but are relatively expensive and have pressure limitations.

(6) Pyrotechnic actuators do not have critical pressure limitations and can be less expensive than solenoids. Pyrotechnic actuators have limited water flow capabilities that can be improved.

(7) Adding an on-off feature to actuators significantly increases cost and complexity of the given device.

RECOMMENDATIONS

(1) The unisensor analog fire detector should be designed for installation in a controlled fire test room. The design should be refined to reduce the dependence of the rate-of-rise sensitivity on the ambient temperature and to reduce cost. Operation of the device should be verified under full-scale conditions simulating residential fires.

(2) The digital processing electronics of the counting digital detector should be designed into a single CMOS integrated circuit. The operation of the device should then be verified under full scale conditions simulating residential fires.

(3) The solenoid valve and pyrotechnic valve and respective interfacing circuits should be refined in design and compared in cost, water flow, and hydrostatic sealing performance. The best resulting actuator should be built and tested in conjunction with the above full-scale detector tests.

(4) A market prototype electronic residential sprinkling system should be designed including water meter, piping, sidewall sprinkler head/valve, power connection, power supply, wiring, detector, and detector/valve interface circuit. Installation and parts costs should be minimized and estimated. Life cycle costs should be estimated. Ancillary alarm capabilities should be explored.

(5) A Nitinol link sprinkler should be designed for installation in a full-scale controlled fire test room. Operation of the device should be verified under varied conditions simulating residential fires. The hardware should be as small as practical, without compromising thermal sensitivity or water flow and hydrostatic sealing capabilities.

(6) An optimal Nitinol wire and alloy should be developed to provide maximal useful work in the range of 125°to 150°F. Suggested detection wire size is 0.041 in dia. for use in activating typical (approximately 1/4-in. dia. water flow passage) residential sprinkler heads.

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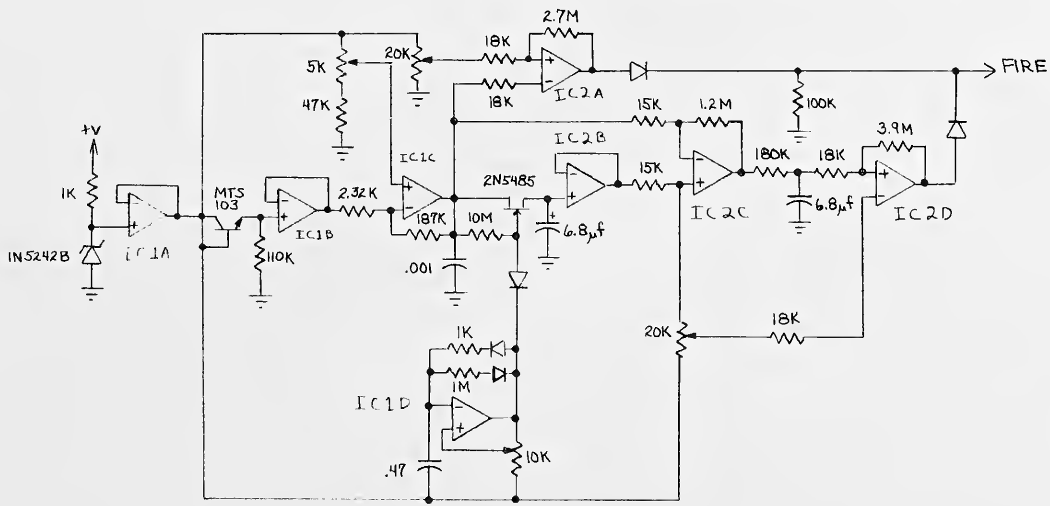
APPENDIX A. CIRCUIT SCHEMATIC AND PARTS LIST FOR THE UNISENSOR FIRE DECTECTOR

The circuit used to implement the UNISENSOR fire detector is shown in Figure A-1. In this circuit, a Motorola MTS-103 temperature sensing transistor was used. The base-emitter voltage of the MTS-103 is very nearly a linear function of temperature. The IC1A circuit is used to provide: (1) bias for the MTS-103 and (2) reference voltage for the comparators (IC2A and IC2D), the scale center adjustment (IC1C), and the sample and hold oscillator (IC1D). Note that differentiation was effected with an oscillator (IC1D), a sample and hold (IC2B), and a differential amplifier (IC2C). The threshold comparator is IC2A, and the rate-of-rise comparator is IC2D. Two diodes and a pull-down resistor perform the OR-ing function. The parts list for this circuit is shown in Table A-1.

TABLE A-1. UNISENSOR FIRE DETECTOR PARTS/PRICE LIST

DESC	Part	1-99	100-999	QNTY
Op-amp	MLM2902P	1.40	1.00	2
Zener 12V	IN5242B	.42	.30	1
Sensor	MTS105	.60	.40	1
Pots.	2-20k; 1-5k; 1-10k	.54	.46	4
Resistors	1/4W 10%	.15	.04	20
Diodes	IN914	.25	.19	5
FET	2N5485	.51	.35	1
Caps.	.001MF	.25	.10	1
Caps.	6.8MF	.80	.30	2
	Total Parts	$12.59	7.04	

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



APPLICATION			
THIS ITEM IS USED ON SUBASSEMBLIES			
DRAWING NO.	PER ASSY	NO.OF ASSYS	TOTAL
TO MAKE FINAL ASSEMBLY			TOTAL REQ'D.

DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES. TOLERANCES ARE:

.XX = .XXXX =

.XXX= ANGLES=

MATERIAL & TREATMENT

SIGNATURE	DIV.	DATE
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DRAFTING APPD.		
DESIGN APPD.		
APPD.		
PROJECT APPD.		
SPECIAL APPD.		

Battelle
Columbus Laboratories

505 King Avenue
Columbus, Ohio 43201
Telephone (614) 299-3151

TITLE

UNISENSOR FIRE DETECTOR

SIZE	CODE IDENT. NO.	DIV. NO.	DWG. NO.	REV.
A	79986		-	
SCALE	ACCT.		SHEET	

CAT. 294163 FORM D-5 12-73

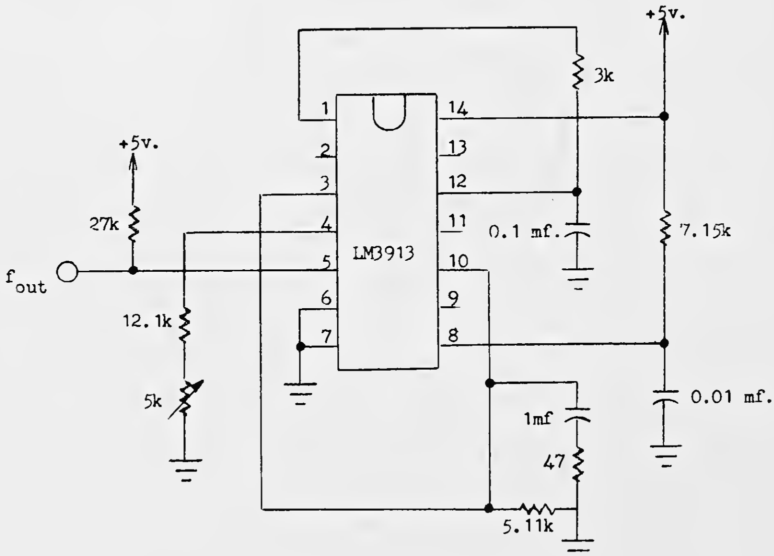
APPENDIX B. CIRCUIT SCHEMATIC FOR THE COUNTING DIGITAL FIRE DETECTOR

The temperature-to-frequency converter circuit was based around a National Semiconductor LM3913 integrated circuit. The circuit schematic is shown in Figure B-1, and Figure B-2 shows the frequency output as a function of temperature. The output (fout) of the circuit is TTL compatible, and it provides a clock input to the sixteen bit up/down counter of the digital processing circuit shown in Figure B-3. The sixteen bit counter is implemented using 74191 integrated circuits. System timing is generated by the Op-amp and the J-K flip-flop. D type flip-flops are used to implement a six bit shift register that controls the system functions. The comparison is done by the gate level decoding circuit. Finally, S-R flip-flops are used to store the RR and TM detect status.

We do not recommend marketing of the shown TTL implementation of the counting digital fire detector. For economic reasons, all of the digital processing circuitry should be designed onto a single CMOS chip. Because of this, a parts list is not shown.

APPLICATION			
THIS ITEM IS USED ON SUB ASSEMBLIES			
DRAWING NO.	PER ASSY	NO. OF ASSYS	TOTAL
TO MAKE FINAL ASSEMBLY			TOTAL REQ'D.

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



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APPD.		
PROJECT APPD.		
SPECIAL APPD.		

Battelle
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201
Telephone (614) 424-6424

TITLE

Temperature to Frequency Converter

SIZE	CODE IDENT. NO.	DIV. NO.	DWG. NO.	REV.
A	79986			

SCALE	ACCT.	SHEET

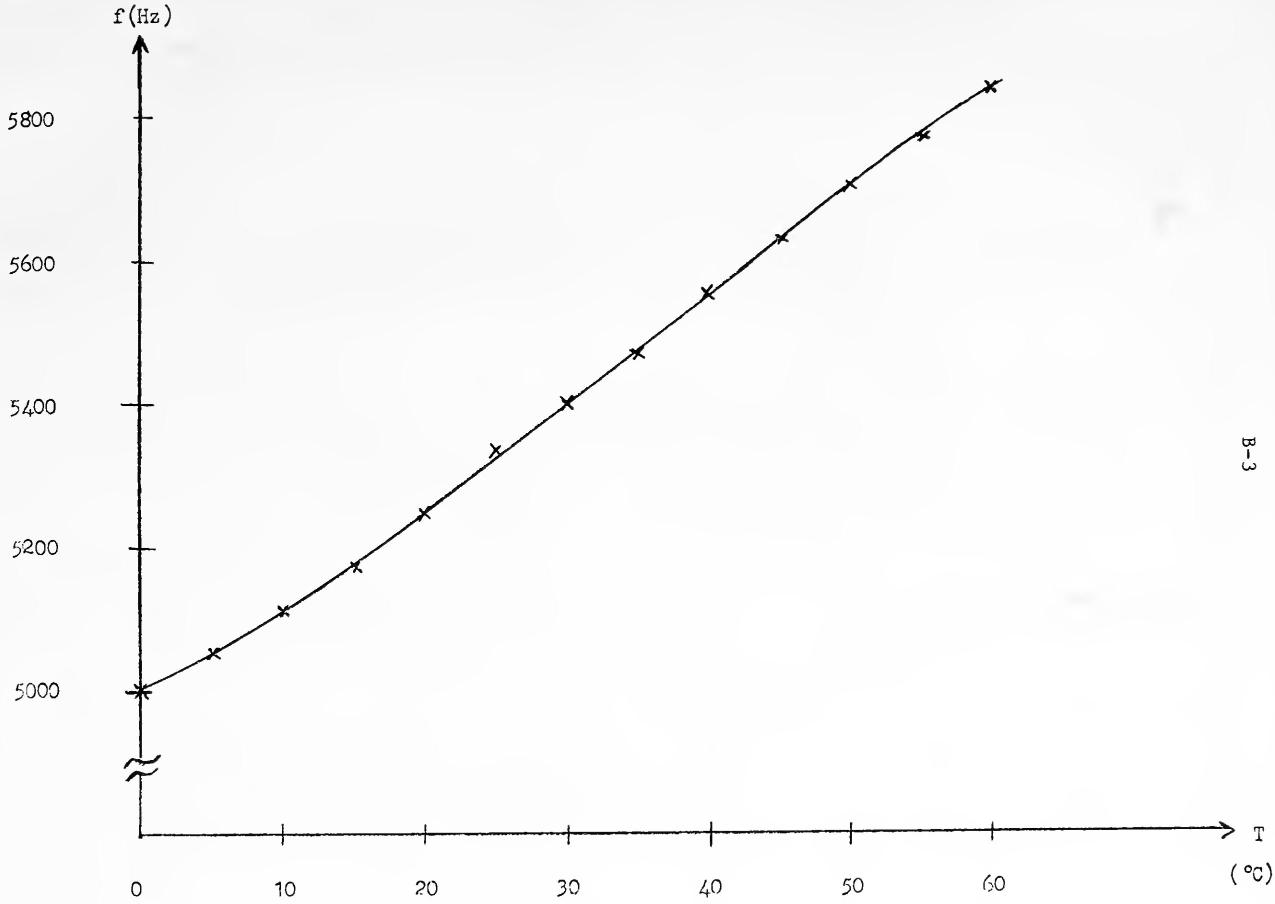
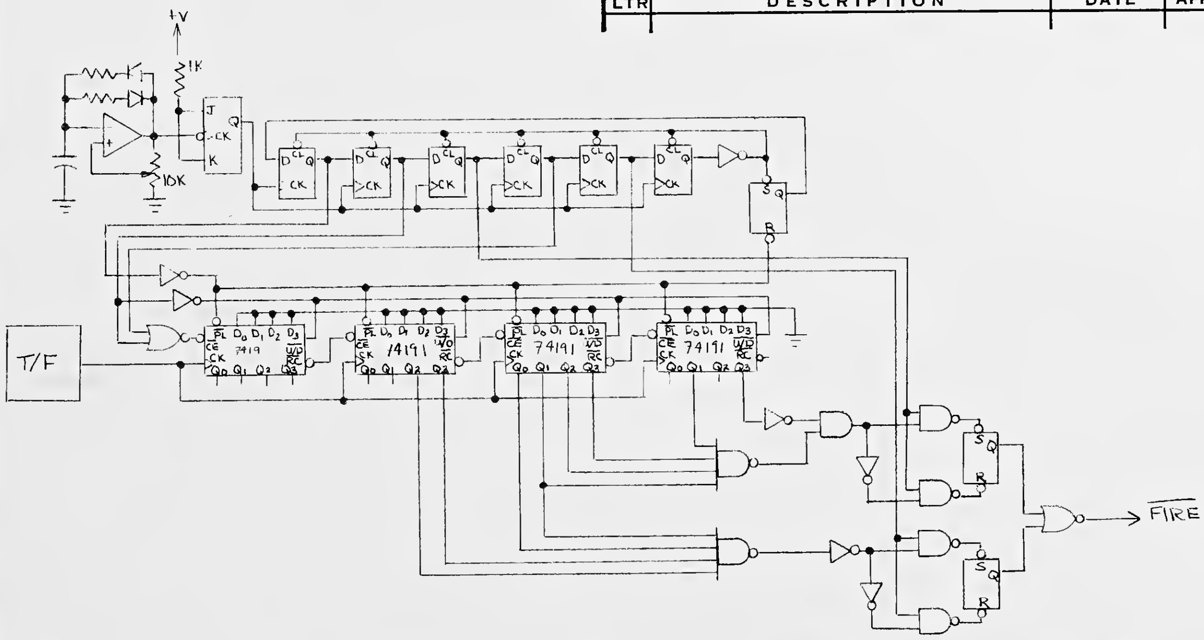


FIGURE B-2. OBSERVED TEMPERATURE AND FREQUENCY FOR THE TEMPERATURE-TO-FREQUENCY CONVERTER CIRCUIT

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



APPLICATION			
THIS ITEM IS USED ON SUBASSEMBLIES			
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TO MAKE FINAL ASSEMBLY			TOTAL REQ'D.

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Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201
Telephone (614) 299-3151

TITLE
Counting Digital Fire Detector

SIZE	CODE IDENT. NO.	DIV. NO.	DWG. NO.	REV.
A	79986		-	
SCALE	ACCT.		SHEET	

CAT. 294163 FORM D-5 12-73

APPENDIX C. CIRCUIT SCHEMATICS AND PARTS LISTS FOR THE PYROTECHNIC AND SOLENOID VALVE INTERFACE NETWORKS

Figure C-1 Shows the schematic of the solenoid valve interface circuit. The detector FIRE signal is low-pass filtered with the input RC network. The filtered signal is amplified by a 2N2925 transistor and used to charge the 100 μF capacitor. The capacitor and all parallel resistors (i.e. leakage currents) act as a timing circuit which begins timing when the input signal goes low and the 2N2925 transistor turns off. Op-amp IC1A is used to buffer the capacitor voltage, which is then input to a comparator (IC1B). The comparator controls a switch (MJE520), which in turn controls the solenoid valve. The component cost and parts list for this circuit is shown in Table C-1.

The detector to pyrotechnic valve interface is shown in Figure C-2. This circuit is very similar to the one described above, with only a few differences. Note that, now, two complementary switches are wired in series from the plus supply to ground. A large electrolytic is connected to the common point of the switches. The effect of this network is to provide a positive pulse at the ouput as the comparator (IC1B) turns on the positive-connected MJE520. When the comparator output goes low, the ground-connected MJE520 turns on, causing the capacitor to discharge, and a negative pulse appears at the ouput. In other words, the capacitor-coupled complementary output stage multiplexes the ON and OFF commands onto a single conductor. These commands can then be easily routed to their respective pyrotechnic squibs with the use of two diodes. The components cost and parts list for this circuit is shown in Table C-2.

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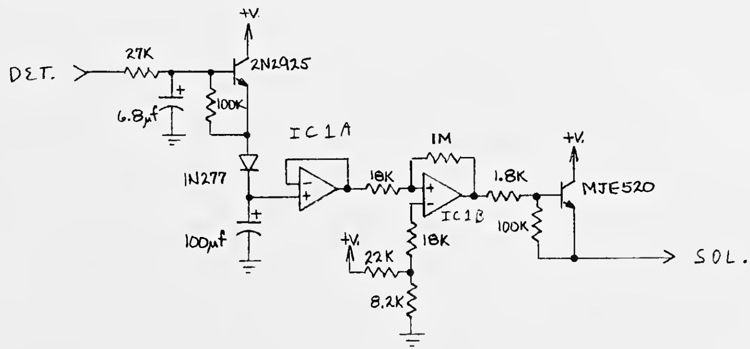
LTR	DESCRIPTION	DATE	APPROVED



APPLICATION			
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DRAWING NO.	PER ASSY	NO.OF ASSYS	TOTAL
TO MAKE FINAL ASSEMBLY			TOTAL REQ'D.

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TITLE
Detector to Solenoid Valve Interface

SIZE	CODE IDENT. NO.	DIV. NO.	DWG. NO.	REV.
A	79986		-	

SCALE	ACCT.	SHEET

CAT. 294163 FORM D-5 12-73

TABLE C-1. SOLENOID VALVE ACTUATOR PARTS LIST

DESC	Part	1-99	100-999	QNTY
Xistor	MPSA20	.26	.16	1
Xistor	MJE520	.55	.41	1
Diode	IN4001	.25	.19	2
Op-amp	MC1458P1	.59	.40	1
Resistors	1/4W 10%	.15	.04	9
Caps.	100MF 30VDC	1.01	.38	1
Caps.	6.8MF 30VDC	.31	.13	1
	Total	$ 4.57	2.22	

TABLE C-2. PYROTECHNIC ACTUATOR PARTS/PRICE LIST

DESC	Part	1-99	100-999	QNTY
Xistor	MPSA20	.26	.16	2
Xistor	MJE520	.55	.41	2
Diode	IN4001	.25	.19	4
Op-amp	MC1458P1	.59	.40	1
Resistors	1/4W 10%	.15	.04	12
Caps.	500MF 30VDC	1.21	.48	1
Caps.	3MF 30VDC	3.71	1.50	1
Caps.	6.8MF 30VDC	.31	.13	1
	Total Parts	$10.24	4.89	1

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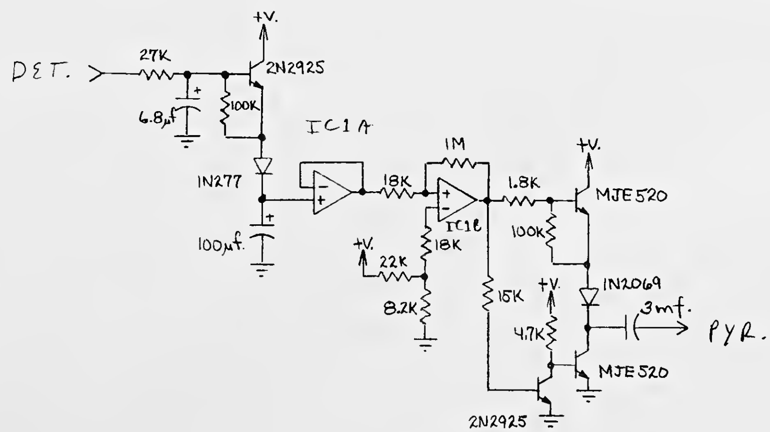

APPLICATION			
THIS ITEM IS USED ON SUBASSEMBLIES			
DRAWING NO.	PER ASSY	NO. OF ASSYS	TOTAL
TO MAKE FINAL ASSEMBLY			TOTAL REQ'D.

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MATERIAL & TREATMENT

SIGNATURE	DIV.	DATE
DRAWN BY TEMarquis	652	17Dec79
DRAFTING APPO.		
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505 King Avenue
Columbus, Ohio 43201
Telephone (614) 299-3151

TITLE
Detector to Pyrotechnic Valve Interface

SIZE	CODE IDENT. NO.	DIV. NO.	DWG. NO.	REV.
A	79986		-	

SCALE	ACCT.	SHEET

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